

**Geophysical, Geochemical and Arable Crop Responses to
Archaeological Sites in the Upper Clyde Valley, Scotland**

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Abstract

This thesis considers the geochemical links between geophysical survey results from, and responses of barley crop growth to, the existence of plough-levelled archaeological sites. It takes as a starting point the results of magnetic and resistivity surveys undertaken at three sites in the Upper Clyde Valley, Lanarkshire, Scotland. Two of the three sites produced geophysical results that closely matched the evidence for archaeological remains recorded using oblique aerial photography. The third site was largely unresponsive to geophysical prospection techniques. These mixed responses prompted a closer examination of why barley crops respond to plough-levelled remains, and why the geophysical data gathered tend to correlate with the growth responses.

To allow an examination of the growth responses, a series of pot-base growth experiments were carried out under glasshouse conditions, and these were followed up by ICP-MS analysis of the plants and the archaeological soils in which they had grown, in an attempt to link any changes in elemental compositions with the growth responses, and to the geophysical responses recorded at the soil sampling points or for the features from which the soils were taken.

The results of the experimental work revealed that although soil moisture content has a role in the development of both crop marks and geophysical anomalies, other factors are also involved, including changes in elemental concentrations in soils and plant material, soil pH changes and the redox potential of the archaeological soils.

Declaration

Except where specific reference is made to other sources, the work presented here in this thesis is the original work of the author. It has not been submitted in part or in whole, for any other degree.

Lorna Sharpe

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“We’re glad it’s all over”!

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Chapter 1: Introduction and Aims

1.1 Introduction

Crop marks, that under favourable conditions develop above buried archaeological remains, have come to be regarded as one of the most effective and efficient methods of detecting and cataloguing the vast number of archaeological sites present in the modern landscape (Riley 1987, 15; Maxwell 1983, 27-39, 1978, 38; Hanson and Macinnes 1991, 155 Macinnes 1983; Driscoll 1987). Geophysical survey, developed since the 1950's for archaeology, has also proved its worth as a valuable remote sensing technique that allows a better knowledge of the undisturbed subsurface (Aitken 1974; Clark 1990; Scollar *et al* 1990). This thesis examines in detail the link between these two remote sensing techniques, which lies in the domain of soil chemical processes, and aims to develop a better understanding of why certain responses are recorded at plough-truncated archaeological sites. This brings into play and introduces the use of a third method of prospection: the geochemical analysis of archaeological soils. Geochemical analysis has also been applied to archaeological sites since the 1950's. In most cases this has been restricted to the examination of phosphate concentrations across sites, often very successfully used in conjunction with magnetic susceptibility measurements to facilitate identification of separate functional areas at, for example, settlement sites (Cavanagh, Hirst and Litton 1988; Conway 1983), but latterly moves have been made towards a multi-element approach to site evaluation. This aspect of site sampling is still in its infancy as an archaeological application, but much promising work has been undertaken (Entwistle *et al* 1998; 2000; Wilson *et al* in prep). This thesis seeks to break down the traditionally compartmentalised approach to site evaluation in which aerial photography, geophysical and geochemical survey tend to be considered and undertaken separately. The theoretical basis for this homogenised approach is outlined and then applied to a series of responses recorded during aerial reconnaissance and geophysical investigation of three case study sites. These are located in the Upper Clyde Valley, Lanarkshire, in southern Scotland, where the fieldwork component of a five-year investigation into the evolution of an archaeological landscape drew to a close in May 2001 (see Chapter 4; Hanson and Sharpe in prep).

1.2 Aims and Objectives

The aim of this thesis is to examine closely the ways in which archaeological remains buried beneath ploughsoil reveal themselves. Specifically the work tests certain hypotheses, examining critically traditional interpretations which emphasise the importance of moisture stress in the appearance of crop marks, and postulates other mechanisms that link the results of aerial photography and geophysics. I wish to test the hypothesis that the occurrence of crop marks over a buried site, and the geophysical responses to it, are both related to the chemical properties of those remains. Differential plant growth occurs over certain sites, and this is usually ascribed to there being differential amounts of water available to the plants in the soil (see Chapter 2). It is proposed here that there are also different elemental levels of nutrients available to the crop plants. Just as a pot plant will produce a burst of lush green foliage following a liquid feed of vital nutrients, so might this effect be seen in the growth of crops over a ditch or other such feature on an archaeological site. The fundamental question is whether this is simply because these plants have more water available to them, the standard interpretation applied to archaeological crop marks, and so are better able to exploit the available nutrient pool. Alternatively, are there differing amounts of certain elements available for uptake in different areas of the buried site? In other words, are certain elements enriched or depleted below the ground because of past human activity in the area? If this is the case, it should be possible to determine which individual nutrients are involved.

The examination of the geophysical and crop responses is facilitated by the use of chemical analysis of soil samples taken from three of the four case study sites, and of barley plants (*hordeum sp.*) grown in the same soils, but under regulated conditions. By looking at the elemental compositions of the plants and soils in isolation, patterns in the spatial distribution of certain elements can be recognised, and linked to both crop growth and geophysical responses. While the survey results are obviously important in their own right, this allows an interpretation of the datasets relative to the elemental distributions, in addition to simply a consideration of what archaeological features areas of anomalous growth or response may represent. In this way, I hope to be able to develop a better understanding of why archaeological crop mark sites appear, and how this links to the geophysical responses. The study should also allow an understanding of whether this chemical aspect of the site's responses is an anthropogenic or pedological phenomenon.

This question would be equally valid if asked of the responses recorded geophysically at a site. Resistivity responses record the ease with which an electrical current can flow through the ground. It is commonly known that water allows electricity to be conducted, whereas the movement of an electrical current is impeded in dry media (Clark 1996; Scollar *et al*; Gaffney and Gater 2003, 26). This is why resistivity survey gives classic high-resistance responses to, for example, buried stone walls, and low-resistance figures are seen across water-saturated and humic media such as those found in ditches and midden deposits. What is often overlooked in this simplistic approach to the interpretation of resistivity data is the role that the chemical elements play in the passage of electrical current. On an atomic level, electrical current is the movement of electrons through a conducting medium. Pure water is a tightly bonded molecule, and electron transfer is not easy between water molecules for this reason. Current will flow more easily in an aqueous solution where there are dissolved electrolytes, that is substances that produce ions when they dissociate in water (Ebbing 1987, 324). This is good news for geophysicists because soil water is not pure water; it is a complex solution of plant and microbial nutrients held in a delicate equilibrium of ions and molecules. The soil solution represents a complex balance between water content, pH, and organic and inorganic components of the soil held in solution (Rowell 1994, 79). This leads one to conclude that as electrolytes in the soil solution must affect the passage of electrical current, what is dissolved or held in the soil must affect the results of resistivity survey.

Magnetic survey can be viewed in much the same way. Iron is the element that plays the most significant role in magnetic survey (Chapter 2). Fortunately, this element is reasonably abundant in rocks and soils, making up around 6% of the Earth's crust (Clark 1990, 64). It is not merely a question of iron being present in the soil, but the form that it takes is most important for magnetic surveys. To enable features to be detected, the materials filling or comprising them must have an enhanced magnetic susceptibility compared to the surrounding soil. Magnetic susceptibility is an indicator of the concentration of magnetic minerals in a medium, particularly magnetite (Keary and Brooks 1991). An enhanced susceptibility develops when iron oxides are converted to maghaemite, a strongly ferrimagnetic form, during heating or, less importantly, fermentation processes. The degree to which magnetic enhancement progresses depends partly on the concentration of the iron oxides in the soils that are capable of enhancement. This is a function of the geological strata or drift deposits from which the soils are derived. The degree of enhancement also depends on the length of time that the archaeological site was occupied, in part determining

the amount of anthropogenic activity, such as the lighting of fires, to which the soils have been subjected (Tite 1972). These mechanisms will be discussed more fully in Chapter 2.

The properties of iron are fortuitous in another way, as iron is an element that begins to illustrate the reason for this study. It is the basis of magnetic survey, and in its ionic form is one of the ions present in soil that contribute towards soil conductivity (Rowell 1994, 285). It is also an essential element for plant growth, albeit a microelement, that is, one needed in small concentrations. This interplay between common factors such as iron affecting the three methods of site investigation will form the basis of this study.

Specifically then, the aims of this thesis are to gather data from aerial, geophysical and geochemical investigations and consider the physical and chemical causes of the crop markings and geophysical anomalies. It is hoped that this approach will allow the development of a better understanding of the way in which crop marks and geophysical anomalies arise, and whether there are correlations between the two that can be explained chemically. This leads to a stage where the possibility of developing novel, non-destructive sampling strategies based on the outcome of this work can be assessed. This study may also provide insight into the way the sites are preserved, and how we can improve our prospection methods. Often the pre-excavation activities undertaken at a site are concentrated on singular or similar methods. Aerial photographs are examined or geophysical techniques are employed. Normally one would not look, for example, at geophysical plots with reference to the crop marks arising from a site, let alone geochemical results in relation to the aerial photographs. The potential data that can be gathered from a combined interpretation of these results is often compartmentalised, as discussed earlier, and not fully exploited. This work follows on from that undertaken routinely at many archaeological sites throughout Britain, that become the focus of research and rescue works. Aerial, geophysical and geochemical investigations in themselves are not unique to this assessment of our archaeological heritage. This thesis moves away from the purely archaeological analysis of sites, and has a more scientific bias. Uniquely, it asks the following questions:

- Why do crop marks form?
- Why in two of the three case studies presented in Chapter 5 do the crop mark responses coincide so closely with the geophysical responses?

- Are there geochemical differences that can account for the responses that are common to all of the remote sensing techniques applied at these and other sites?
- What is the significance of this approach for future prospection methodologies?

1.3 Structure of the Thesis

This chapter has defined the aims of the thesis and its context. The theoretical and methodological basis for the work is set out in Chapters 2 and 3 respectively. The development and possible causes of archaeological crop marks are discussed in detail, as are the geophysical survey techniques and geochemical investigation methodologies. In Chapter 4, the area in which the work is set is introduced. This chapter begins with a look at the geological and geographical background of the Upper Clyde Valley. Moving on to the landscape and the archaeological resource in the area, it details the three sites that are the focus for the investigations required for this thesis. The case studies are presented in Chapter 5, and the experimental work in Chapter 6, after which, in Chapter 7, I will summarise the results of the study, and attempt to apply these results to the broader question of how sites are preserved and located today.

Chapter 2: Towards An Integrated Approach: The Theoretical Background

2.1 Introduction

This chapter sets the theoretical background for the thesis, which challenges the conventional view of how crop marks form at archaeological sites. Therefore, there is a need to examine closely the traditional explanations for crop mark formation and, in addition, to present other factors that are thought to be involved in the process. Accordingly, aerial photography and the appearance of crop marks are discussed first in this chapter, followed by an introduction to the theoretical background to the geophysical techniques (magnetometry and electrical resistivity) that were applied to three Case Studies, which are introduced in Chapter 4. In contrast to the alternative view taken of the way crop marks appear, geophysical theory and the way that it works is not challenged here. The magnetic properties of the earth and its materials are long-established and proven experimentally (Scollar *et al* 1990, 384-7; Aitken 1974, 135-148, 189-90, 207-34; Keary and Brookes 1991), as is the behaviour of electricity in the earth and other media (Ryan 1986; Scollar *et al* 1990, 307-72; Aitken 1974, 267-9; Keary and Brookes 1991). As such, and because of the large body of published information on geophysical theory, the need for an in-depth examination of it here is not considered necessary.

The thesis considers specifically the factors that link crop mark formation and geophysical responses. It is proposed here that the link lies in the behaviour and movement of elements held in solution in the soil at an atomic level. This examination, then, requires a consideration of soil and its elemental composition and particularly of electromagnetic theory as it pertains to the movement of solutes within the soil. This is where the link is to be found between the differential growth of barley crops that make up crop marks in the case studies, and the corresponding geophysical responses.

I wish to explore the hypothesis that there are chemical differences in the archaeological features that result in enhanced and/or depleted levels of elements that are required for plant nutrition, and that this accounts for the differential vegetation growth. These localised differences in elemental concentrations must in turn result in differences in

dissociated ionic concentrations in the soil water. This relative abundance or depletion of ions and associated free electrons will then increase or reduce the ease with which electrical currents can move in the soil, and in turn effect changes in the electromagnetic properties of the subsurface. Therefore the link between aerial and geophysical prospection results is expected to lie in changing elemental concentrations that will be measurable in soil samples taken from different buried archaeological features.

A more sensitive measure of soil nutrient status is achievable by examining the levels of nutrient actually taken up by growing plants, and this is in effect the information that a crop mark presents qualitatively. Experimental work for this thesis (see Chapter 3) includes an attempt to quantify this uptake by analysing barley plants grown in soils from archaeological contexts and areas of known geophysical responses at three Case Studies.

Finally, there must be a consideration of why there are measurable elemental differences in different archaeological contexts. This work provides the information about whether the differences are likely to be natural, that is due to different soil properties, or whether they are anthropogenic, that is changes in elemental concentrations as a direct result of past human activity. Once a soil profile is disturbed, pedological processes continue to act on the altered profile, which results in locally altered soil properties in a long-abandoned site. For example, different moisture-holding capacities may develop due to the presence of a more humic soil at the site of an abandoned midden, which would then affect soil temperature and pH values (White 1987, 43). Both pH and soil temperature are known to affect the availability of elements for plant uptake and the mobility of, and equilibria between, different elements in the soil solution (Marschner 1995, 486; Scollar *et al* 1990, 19). Alternatively, it may be possible to identify actual elemental differences present that are due to anthropogenic activity. For example, work currently in progress at Stirling University (Wilson *et al* in prep) on the identification of geochemical markers for functional areas at abandoned historic farmsteadings has identified a suite of elements that consistently appear at enhanced levels. Certain elements are consistently high for certain of the features examined, such as calcium in hearths, for sites as disparate as Mainland Orkney, North Yorkshire and Wales. If this area of geochemical assessment is as promising as it appears to be, it opens up the possibility of developing new ways of prospecting for archaeological sites. This would exploit what would effectively be newly identified marker elements in a similar way to that in which phosphate analysis is now used. Taken together with geophysical and aerial reconnaissance it has the potential to

provide a very powerful, integrated, non-invasive tool for interpreting even plough-levelled sites. This is examined in Chapter 6, where the results of all of the work undertaken are brought together.

This is a long chapter, and necessarily so as it covers a wide range of concepts taken from several disciplines. To guide the reader, the order in which the main sections are presented are as follows: a close examination of the current thinking on how archaeological crop marks appear, together with an alternative approach, moves on to a brief description of soil chemistry as it pertains to crop mark formation. Plant responses to growth conditions are examined along with the role of some of the main plant nutrients before moving to the link between crop mark and geophysical anomalies. This link is explored through electromagnetic theory, which then leads into a consideration of geophysical theory as is relevant to this thesis. In the concluding section the strands from each section are brought together to present the hypothesis that will be explored in the remaining chapters.

2.2 Aerial Photography

“If each plant, for example, can be considered a sensor, then the number of ‘measurements’ made of the subsoil in the area of the photographs is very high indeed.”

Scollar *et al* 1990, 28

Introduction

This section considers only those aspects of archaeological aerial photography that concern the appearance of crop marks. The subjects of site discovery, recording and interpretation have been extensively studied (eg Riley 1980, 5-9; Crawford 1929, 3-5; Wilson 1982, 27-69, 71-2; Scollar 1990, 26-122; Darvill 1996, 1-10) as have the technical aspects of recording, flying and transcription of the resulting photography (Stoertz 1997, 9-11; Riley 1990, 33 - 47; 1996, 49-55; Whimster 1990; Pickering 1980, 50 – 52; Wilson 1982, 195-202; Haigh, Kisch and Jones 1983). However, the reasons why crop marks appear, and more specifically the soil properties and conditions responsible for their appearance, have been little considered.

Beginning with a brief introduction to the development of aerial archaeology in Britain and Europe, this section moves quickly on to the assessment of current knowledge and theories on the conditions under which archaeological crop marks are formed.

Background

Riley, writing of the development of aerial photography for archaeology, describes the primary campaigns in Western Europe after the First World War as “information explosions” (Riley 1987, 15). This can be seen to be the case in almost every area that has been photographed from the air for these purposes (Maxwell 1983, 27- 39; Hanson and Macinnes 1991, 155). Aerial reconnaissance for archaeology has been systematically used in Britain since the 1920’s and in many parts of Western Europe since the late 1950’s. This prospecting method is most successful, having resulted in the detection of more buried sites than all of the other prospection methods combined (Scollar *et al* 1990, 26). Different modes of information recovery are well-established within aerial photography, but by far the most important are crop marks. The Clyde Valley, the setting for the crop mark sites used in this thesis, is no exception, as Maxwell acknowledged (1978, 38) during his preparations for the RCAHMS’ Lanarkshire Inventory of Prehistoric and Roman remains (RCAHMS 1978). In this case, although RCAHMS only began systematic flying in the mid-1970s, around 20% of all the sites recorded in the Lanarkshire volume were located using aerial reconnaissance. Around two thirds of these were discovered during flights by RCAHMS and CUCAP fliers, which specifically set out to record archaeological sites, and the rest were discovered on vertical photographs taken by the RAF. The archaeologically directed sorties took place over a period of more than three decades. The original percentage of sites discovered from the air is actually low for Lanarkshire because the sorties were carried out mainly by J K St Joseph from CUCAP. The proportion of sites now recorded as crop marks has vastly increased, a direct consequence of increased reconnaissance by local fliers such as Prof. Bill Hanson. A comparison with later RCAHMS inventories, for example the South-East Perthshire volume (RCAHMS 1994) gives a clear indication of the positive impact on the knowledge base of an archaeological landscape subject to an intensive, focussed programme of reconnaissance.

2.3 What Causes Crop marks to Occur?

The Simple Consensus View

Archaeological crop marks are most commonly recorded in cereal crops, notably barley, during warm, dry summer months when a soil moisture deficit (SMD) has developed, ie when evaporation from the ground and transpiration from the growing vegetation cover exceed the amount of rain falling. Consequently, the common consensus amongst archaeologists involved in aerial reconnaissance is that the appearance of crop marks is governed by the amount of available water in the ground. Cereal crops are most favourable for crop mark formation because they are deep-rooted, the individual plants cover a relatively small area compared to other, broad-leaved agricultural crops, and the sowing density of the cereals is comparatively high. This allows good definition of the underlying sites based on the growth responses that develop, in effect giving good resolution due to the small 'pixel size'. This is especially true for barley, which is said to show archaeological crop marks best of all the cereal crops. Having the largest leaf area index (LAI) per plant, and so increased surface area for transpiration, it is more sensitive to drought than the other narrower-leaved cereals. The LAI is defined as the area of one leaf surface in a crop stand covering a unit area of soil (Jones and Evans 1975, 2). This large LAI also renders the individual plants that are affected by differential growth more visible from the air than those of other cereal crops (Riley 1987, 38), allowing differences in leaf colour, number and size within the crop to be clearly seen.

Crop marks form where plants overlies archaeological features that are assumed to retain soil moisture differentially compared to the surrounding 'bulk' crop. Consequently, if plants are growing over a cut feature, such as a ditch, the increased depth of topsoil there holds more moisture than in the rest of the field and so the crop growth is likely to be enhanced, particularly during periods when water stress develops. The area of enhanced growth is visible from the air and is termed a positive crop mark (Riley 1987, 6; Allen 1984, 43). Conversely, any plants growing above building foundations, ploughed out bank remains or areas of compacted ground experience localised water deficits. There is less available water because there is less moisture retentive soil and the plants exhibit symptoms of water deficit and related nutrient imbalances in these areas. The marks associated with these conditions are termed negative crop marks, and are generally less common than positive marks (Riley 1996, 25; Scollar *et al* 1990, 52, but see Hanson and Oltean 2003). The plants forming positive crop marks are characteristically taller and

darker green with lush, healthy foliage. They tend to produce more tillers and have a more dense growth habit than the surrounding crop plants, both of which increase LAI. Plants associated with negative crop markings tend to be paler green, produce less-dense growth, which is not as tall, with fewer tillers, giving a lighter coloured appearance from the air.

Towards the end of the growing season, plants forming positive crop marks tend to reach maturity more slowly than the surrounding plants, being well-nourished and having good reserves of water to exploit (Darvill 1996, 7; Riley 1987, 6). Cereal maturity is driven by three factors: sunlight, which triggers developmental stages; nitrogen, an excess of which prolongs the life of leaves; and water, which has the same effect as nitrogen (D P Moss pers comm), with droughted plants turning from green to yellow and setting seed earlier. This can result in a phenomenon known as crop mark reversal. As the term suggests, this involves a change in the appearance of the crop mark relative to the rest of the crop. First the positive growth appears darker green against the now comparatively lighter hue of the rest of the field, as the majority of the crop ripens and dies. The effect then continues to be visible when the whole crop ripens, with the positive marks then appearing lighter yellow in colour compared to the rest of the darker yellow crop. This reversal is ascribed to the taller, denser growth habit of the plants comprising the crop mark (Riley 1996, 28; 1987, 6). The difference may remain visible even in stubble, confirming the density difference between crop mark and remaining plants.

Crop mark formation is favoured in certain areas relative to others, depending on factors associated with the geology of the area, the soil conditions and crop and weather patterns. For example, crop marks are less likely to occur on clay-rich soils and clay subsoils because of their relatively large water holding capacity (Riley 1987, 35, 37). This is illustrated in the crop marks produced at Case Study 3 (Chapter 5). Crop marks form more commonly on sands and gravels, and this is assumed to be due to the free-draining nature of these sediments, which allow water deficits to develop more easily. The high number of crop marks recorded on river gravels, for example along the River Thames, is testament to this (Riley 1987, 83-85; Darvill 1996, 241-5; Allen 1984, 74-5; Bradford 1984, 19-25; Stanley 1981, 7-12; Crawford 1927, 469-74). A similar situation has been recorded on the gravels of the River Trent (Riley 1987, 35). Some geological settings are known to be more conducive to the development of crop marks, for example the Cretaceous Chalk of the Yorkshire Wolds (Stoertz 1997), the Lincolnshire Wolds

(Everson 1983, 14-26) and the Bunter Sandstone belt which outcrops in and around Nottinghamshire (Riley 1987, 35-6; 1980, 1). Keuper Marls, associated with clay soils in the same area, have proved to be unproductive. Where sandstones and chalks tend to be porous rocks, allowing free-draining conditions in the overlying soils, marls and certain other rock types, for example crystalline igneous rocks, are much less permeable to water. This is assumed to be the reason for the apparent absence of crop mark sites in areas with underlying geologies such as the Keuper Marl. The adjacent limestones and Coal Measures (comprising cyclic accumulations of sandstone, coal, clay and shale strata) have similarly been found to be less likely to reveal sites as crop marks.

Some climatic conditions are better suited to the appearance of crop marks, and an example of this is the milder weather conditions prevailing along the East Coast of Scotland. A combination of rainfall, temperature and land-use, result in a higher density of sites being identified from the air here than in the North and West of Scotland (Hanson and Macinnes 1991; Hanson forthcoming). This bias in the Scottish crop mark record is further compounded by reconnaissance efforts being more concentrated along the eastern seaboard. This is due to the favourable factors mentioned combined with proximity to the RCAHMS headquarters in Edinburgh, resulting in ease of access logistically and the promise of high productivity in terms of number of sites recorded in relation to flying hours.

Finally, important variables in crop mark appearance associated with the plants themselves include the kind of crop sown and the sowing date (Riley 1987, 6). For example, barley is the best crop for crop mark appearance. However, spring and winter barley crops develop crop marks differently depending on the moisture availability at crucial growth stages, such as germination, tillering or initiation of flowering, factors which are examined in the experimental work associated with this thesis (Chapter 3).

We must accept that there are some areas that do not reveal crop marks (Darvill 1996, 9). It must be remembered that, although aerial photography is one of the most significant contributors to the discovery of new sites, it can only answer questions positively (Scollar *et al* 1990, 32). Absence of sites in a particular area may not mean that there is nothing there, merely that the soil and site properties prevent it from being seen from the air (Hampton 1975, 122-3). An example of this is a comparison carried out by Scollar for one particular undisclosed area that has been examined from the air and on the ground for

almost 30 years. In this briefly mentioned example, the discovery of sites from the two different perspectives resulted in a less than 25% correlation between the survey types. Where ground survey was found to be productive, aerial photographic results were poor, indicating that the aerial view does not constitute the definitive view of a site or a landscape (Scollar *et al* 1990, 32).

Some fliers emphasise the importance of recognising zones that are favourable for the appearance of crop marks to guide reconnaissance, whilst taking into consideration the current state of knowledge regarding the archaeology of that area. In this way, reconnaissance can be directed towards the continued surveillance of areas within favourable zones that have so far not produced crop marks. Under the circumstances the gaps noticeable in unfavourable zones can be regarded only as that, and not an indication of the absence of any past activity (Wilson 1979, 32-6; Scollar *et al* 1990, 33). This raises the question of why these apparently favourable zones do not produce crop marks, assuming that there are archaeological remains present. Lack of crop mark evidence in these areas suggests there are more factors at play than those outlined above. If only climate, geology and crop type were responsible for the appearance of crop marks, prediction of their appearance would be much more reliable.

An Alternative Hypothesis

Without doubt the amount of available ground water is clearly an important factor in the formation of crop marks, and a look at any publication on the subject or any archive will confirm that a large number of sites are recorded in years where droughts are particularly harsh, such as in 1976. The effect of the 1976 drought in Northern Europe was to reveal sites in areas that had been unproductive until that point, and increase the total quantity of known sites in the favourable areas (Scollar *et al* 1990, 33). Similar effects have been noted in Scotland in general, and in Lanarkshire specifically (Maxwell 1978, 38). Citing the period of 1976-77, Maxwell states that in thirty years or more of oblique aerial reconnaissance, this was the most significant period of discovery. During this time surveillance was "more than usually intensive", with 226 hours spent in the skies over the whole of Scotland between 1976 and 1978. The extreme drought allowed over 830 sites to be recorded, whereas the average number of sites usually recorded each year was given as around 670 (Maxwell 1978, 40). Stanley cites 1974 and 1982 as particularly good years for crop mark clarity in the Upper Thames Valley (1981, 12). However, it is not

simply a matter of dry summers resulting in the appearance of large numbers of crop marks. The timing of precipitation events are also important factors. For example, in Scotland below average rainfall in May and June, with a continued dry period into July and August, will tend to produce an above-average record of visible crop marks (M Brown pers comm). Again, this factor is examined in the experiments carried out for this research described in Chapter 3.

Whilst these examples leave no doubt that the increased number of recorded sites reported is a direct consequence of the dry weather, two factors must be considered alongside this apparently clear-cut relationship. Firstly, as indicated by Maxwell, when the weather is dry, air survey is usually intensified, partly because there are expected to be more sites showing, but also because there will be a higher chance of clear skies and generally better conditions which allow higher numbers of reconnaissance flights. More air time must increase the chances of seeing more sites (Miles 1983, 84). There is also the opinion that there is no point in flying more if crop marks are not showing well during initial flights over an area, and that there are regional variations in the weather that should be considered before writing off a year as being bad for crop mark appearance (Prof W Hanson pers comm). It has been stated that “time in the air *per se* will not materially increase the number of crop mark discoveries, but it is difficult to argue the reverse” (M Brown pers comm). Secondly, during a good year not all of the sites recorded are crop marks in the sense discussed here. For example, during the 1976 drought many of the additional sites recorded were *parch marks* in grassland and pasture in the West of Scotland, where it is unusual to record sites under the normal weather conditions of a Scottish summer (Hanson forthcoming). Parch marks, although still strictly crop marks, are usually seen in grass as a consequence of severe drought causing the sward to perish in areas where shallower depths of soil result in even more severe moisture stress (Darvill 1996, 8). This type of crop marking is not considered further here, apart from defining and making the distinction between this type of marking and a negative mark. In a parch mark areas of grass die because there is no water available to sustain life in those areas. In a negative crop mark, not usually associated with grass cover, the vegetation growth is inhibited due to a limiting environmental condition, assumed to be water reserves, but the significant difference is that generally the affected plants do not die. Instead, visual differences in growth between the affected plants and those not subject to the growth-limiting factor are noted. Technically, cereals subject to extreme limiting conditions, such as severe drought resulting in crop failure, would then also be categorised as parch

marks. For the purpose of this thesis, however, and generally in agricultural terms the distinction between parch marks and negative crop marks is that in the former the plants are dead. The regeneration of grass in parched areas is not due to revival of the plants that had died back, but a consequence of their means of vegetative reproduction. This allows certain grasses, which propagate by means of underground roots (rhizomatous grasses) or over- or underground stems (stoloniferous grasses) to reform and maintain the sward. In Scotland, parching in grass tends to occur following below average rainfall in July and August, when there has been no rain for at least two weeks, which is not a common occurrence (M Brown pers comm). So, a combination of more crop marks in arable areas, the ability to record parch marks and more intensive flying effort overall will lead to increased numbers of sites being recorded in hot dry summers. This is not necessarily, then, positive proof that soil moisture levels are the only factor at work in the appearance of archaeologically significant marks in cereal crops. Little reference is made to the results of intensive flying in wet years, and so it is difficult to say whether comparable results could be achieved under traditionally less favourable conditions. This point is demonstrated by Whimster (1983, 104) who in the below-average English summer of 1977 notes that such years can

“...yield discoveries at a rate compatible with that obtained in a particularly good season, such as 1976, even though the total number of crop marks recorded in 1977 (136) was less than a quarter of the total for the preceding year (611). There seems to be no simple explanation of this observation”.

For these reasons, soil moisture differences as a sole cause of the appearance of crop marks should be examined more closely. Most important is the simple fact that soil is a very complex medium, and changes in one of the conditions of such a complex system will always affect other factors. So, whilst soil moisture clearly does play a part in the appearance of markings over archaeological sites, it is not necessarily always the cause, and may turn out never to be the sole cause. Other people have brought this into question; for example, Jones and Evans (1975; 1977; Jones 1979a) have made several important contributions to our knowledge of why crop markings appear. Riley (1996, 27) and Hanson (forthcoming) acknowledge that the cut features over which positive crop marks form represent areas of potential deeper rooting, which hold more reserves not

only of moisture, but also of nutrients. This is discussed in more detail later in this chapter.

Finally, my own experience as a geophysical surveyor of archaeological sites causes me to question the reasons for crop mark formation. Specifically, if the formation of crop marks over a site were solely due to differential water content in the underlying soils, it would be straightforward to explain the results of resistivity survey, which often correlate very closely with aerial reconnaissance results. However, it does not answer the question why magnetic surveys, which should not, according to theory, be affected by the presence of water (geomagnetic surveys of the ocean floor are regularly successfully undertaken), also often produce survey results so similar to the crop marks? This suggests that there are other differences operating in the subsurface, and it is feasible that the differences that cause the magnetic anomalies may also contribute to the formation of crop marks. There are a number of cases, discussed below, where excavations at crop mark sites have uncovered no trace of archaeological remains below ground. This suggests that whatever has caused the enhanced growth remains only in the topsoil. Absence of a record of changes in the soils significant enough to excavate and assign context numbers indicates that the cause of the enhanced growth is clearly not structural or textural. This, combined with the problems of explaining the magnetic responses, begins to suggest a chemical explanation for the enhanced growth of the crop mark plants and anomalous magnetic readings. This idea, which is crucial to the work undertaken here, is explored further below and in Chapter 5, and brought to a conclusion in Chapter 6.

2.4 Evidence of Complexity in Crop Mark Formation

Introduction

There are four generally accepted factors indicated in the formation of archaeological crop marks. These are the roles played by water, both atmospheric and soil; the physical properties of soil; the chemistry of the soil, and physiological effects observed in crop plants forming the marks. Each of these factors is examined below giving the current understanding of crop mark formation as expressed in the published literature. Compartmentalisation of these factors is necessary as a first step to understanding crop mark formation, but it is then essential to take an holistic approach to the question, for, as Scollar *et al* (1990, 50) remind us:

“Of all the passive methods, it is by far the most complex to analyse, being a consequence of the interaction of growing vegetation, soil structure, and climate. Perhaps because of this complexity, there are less quantitative experimental data available than for any physical method, most evidence being based on qualitative observation.”

In Chapter 3 I will outline the experimental design and methods chosen to attempt to begin to redress this lack of quantitative data.

Many workers begin with the basic premise that visible differences appearing in a field must be due to some growth factor that changes suddenly and locally (Jones and Evans 1975, 2). This local change in conditions has the effect of altering the nature of the vegetation growth over a confined area. Simple examples of this, in response to agricultural activity, include uneven fertiliser applications causing areas of dark green enhanced growth, similar to positive archaeological crop marks, where excess fertiliser has been applied. Subsurface drainage systems can be plotted from aerial photographs as herringbone patterns or lines of darker, or occasionally lighter, crop growth due to disturbance of the soil profile through their installation or localised changes in drainage properties. Differential growth can also develop over areas where the subsurface drift or solid geology changes, or where geomorphological features leave traces, such as abandoned river channels or ice crack wedges (Scollar *et al* 1990, 31; Wilson 1982, 141-55). Archaeological crop marks are differentiated from those overlying natural features by their sharply defined edges, which also suggests that they have certain unique properties compared to the other types of mark, even if this is only their deliberate construction. Geological and geomorphological crop marks are also assumed to appear in response to soil moisture differences, and again it is almost certain that this is part of the story. However, abandoned river meanders for example, like archaeological features, undergo changes in the composition of their fills, with fine silts and clays along their inner bends and pebbles and coarser sediments on their outer curves. Geological features would tend to affect drainage on a regional scale, against which the smaller scale geomorphological and archaeological features are set. Some geological strata, however, do affect crop growth. An example of this is a limestone, known as Cornstone, which is present in places in Clydesdale as discrete linear bands, for example outcropping in the bed of the River Clyde between Carmichael Mill and Millhill farm (see Figure 4.1, Chapter 4). This limestone is so called because it buffers the soil pH (a soil that develops

on limestone will have a greater tendency to be alkaline, resulting in enhanced growth of overlying cereal crops. Thus, it can be seen that soil moisture differences are not even the sole explanation for natural crop marks.

However, only the crop marks caused by underlying archaeological sites are of concern here. These can be viewed separately from natural features because they are caused by anthropogenic activity that has affected the local properties of the soil. As such it is possible that traces of the concentrated and repeated actions of these people have left more than a changed soil horizon; that they have left chemical markers of their presence in the soil, which are expressed in the differential growth of the crops. It has been suggested that it is almost impossible to completely destroy a site by normal agricultural means and leave absolutely no trace of past construction in the ground. Even if there are no unnatural materials remaining, at the very least the soil profile will have been disturbed (Scollar *et al* 1990, 37). There is, however, an assumption that the length of time elapsed at some of the earlier sites precludes there being any enhanced non-renewable elements still present in the soil today (Scollar *et al* 1990, 57). However, the successful use of phosphate sampling proves that this is not necessarily the case, and “Each successive phase of human activity modifies the soil record and leaves some trace in the soil” (Entwistle *et al*, in prep). Phosphate analysis and, increasingly, multi-element analysis have been very successfully employed at many sites. Measurement of phosphate levels, the more established methodology, has assisted in defining the limits of habitation, and has aided site location as part of a suite of remote sensing techniques. It is based on the detection of elevated phosphate levels due to past enhancement from organic wastes and burning (eg Bethell & Mate 1989; Cavanagh, Hirst and Litton 1988; Conway 1983; McCawley and McKerrell 1972; Jones and Smith 1979, 14-17).

So, archaeological crop marks (henceforth called just crop marks) are defined as “visible differences in growth caused by buried archaeological remains” (Wilson 2000, 67). Scollar *et al* (1990, 9) state that “The detection of archaeological structures is based on the measurement of a difference or contrast between the properties of the materials which constitute the structures and those of their environments.” This applies to both crop marks and to geophysical results. Unlike the naturally occurring marks, recognition of archaeologically significant features from remotely sensed data relies upon the anomalous areas forming coherent, recognisable patterns (Scollar *et al* 1990, 31). Under certain circumstances the patterns are recognisable as datable site types, such as Roman camps

and fortlets, although generally such interpretations should be made with caution in the absence of any firmly datable evidence from the site concerned. According to Jones and Evans the differences that are measured at individual sites are caused by changes in conditions that result in growth limitations in certain places within the field (1975, 2). This is an interesting approach, as most archaeologists (Jones and Evans are soil scientists) describe crop marks in terms of enhanced growing conditions associated with the underlying archaeology, rather than limiting factors elsewhere in the field. This suggests, for example, an input of nutrients that are unique to the features producing the crop mark. Although the difference is subtle, this in effect changes the emphasis slightly and has an impact on the importance of the reservoir effect versus the enrichment of nutrient elements that archaeological remains may have, as considered below during the discussion on soil depth. This alternative approach suggests that the underlying archaeology affects the cereal growth in a positive way, providing resources that are otherwise somehow limited or limiting in the rest of the field. These resources may be water, nutrients or a combination of both. It becomes important when considering whether this enhancement is due to direct anthropogenic inputs to the soil, or whether it is in effect a cultural (in the plant growth and development sense) factor due, for example, to increased soil depths accumulated in cut features. The approach is taken not only by soil scientists, but has also been suggested by a plant nutritionist (W Fricke pers comm). Fricke suggested enhanced nutritional status as the cause of the crop marks in Case Study 1 (Craigie Burn enclosure, introduced in Chapter 4 and looked at in detail in Chapter 5). This plant nutrition-based approach to the question of crop mark formation is again different to that of the archaeological community. Jones and Evans attribute the visible differences in growth to differences in plant colour, stem height and LAI (1975, 2). They suggest that when considering the reasons for differential growth, the effects of water and nutrient availability are most important, because successful plant growth depends on the satisfaction of metabolic requirements.

Table 2.1 summarises the factors indicated in the formation and appearance of crop marks. Not surprisingly, many of the soil factors listed are the same as those used to describe the soils that comprise archaeological features and form the basis of identification of different contexts during excavation. These then are the first direct links between what can be shown to exist below ground and what causes crop marks to appear above the features. This proves that significant soil changes are at the root of at least the aerial remote sensing responses.

Table 2.1: Factors Responsible for Crop Mark Appearance

Large-Scale Factors	
Solid and/or drift geology	Scollar <i>et al</i> 1990, 32; 1964; Darvill 1996, 7; Riley 1983; 1946; Webster & Hobley 1965
Local climate	Scollar <i>et al</i> 1990, 32; 1964; Jones & Evans 1975, 2; 1977
Drainage	Wilson 1975, 59
pH of groundwater	Wilson 1975, 59
Soil Factors	
SMD	Riley 1987, 27; Wilson 1978, 47; Jones & Evans 1975, 2-3; Jones 1979a; Crawford & Keiller 1928, 6, 107-8; Crawford 1933
Soil type	Riley 1987, 27; Wilson 1978, 47
Soil depth	Wilson 1975, 59; Jones & Evans 1975a, 3; 1975b; Jones 1979a, 657; Darvill 1996; Riley 1983
Soil particle size	Jones & Evans 1975, 4
Structure	Jones & Evans 1975, 4
Stoniness	Jones & Evans 1975, 4; Jones 1979a, 657
Porosity	Jones & Evans 1975, 4
Consistence; degree of compaction	Jones & Evans 1975, 4
Nutrient supply	Jones & Evans 1975, 2; Jones 1979a, 657
Factors that Influence Plant Growth	
Nature of soil mineral fraction	Jones & Evans 1975
Kind and quantity of organic matter	Jones & Evans 1975; Taylor 1979
Macro- and micro-nutrients	Jones & Evans 1975
Nutrient availability in rooting zone	Jones & Evans 1975
Adequate, sufficiently extensive root system	Jones & Evans 1975, 4
Enough water to allow:	
- Nutrient transport to plant uptake sites	Jones & Evans 1975, 4
- Operation of uptake system at root surface	Jones & Evans 1975, 4
- Translocation of nutrients within plant	Jones & Evans 1975, 4
Factors Causing Differential Appearance in the Same Crop Mark from Year to Year	
Availability of water	Jones & Evans 1975, 4
Timing of water availability	Jones & Evans 1975, 8; W Hanson pers comm
Timing of nutrient availability	W Fricke pers comm
Sowing date of crop	Riley 1987, 27; Jones & Evans 1975, 3
Kind of crop grown	Riley 1987, 27; Wilson 1979, 28-32; 1978, 47; Hampton 1975; Jones & Evans 1975, 3
Modern agricultural practice	Scollar <i>et al</i> 1990, 32; Wilson 1978, 47; Wilson 1975, 59-69
Factors Associated with the Underlying Archaeology	
Width and depth of buried features	Miles 1983
Contrast between fills and natural	Miles 1983
Soil factors associated with archaeological materials	Miles 1983

The importance of the relative timing of combinations of the factors indicated in Table 2.1 to the appearance of crop marks is also discussed extensively (Wilson 1978, 47; Scollar *et al* 1990, 32; Riley 1996, 27). It is uncommon for all of the factors to be in place so that the majority of sites present in an area are actually visible at the same time. In fact, the appearance of even well-known crop marks is notoriously sporadic. On an individual site basis, the interplay of the various combinations of these factors over many seasons may not allow a site to be revealed at its best or in its entirety for many years. This indicates the complexity of the factors involved in the appearance of crop marks, even in the same field, under the same cultivation regime and, one would assume, similar drainage conditions and soil properties. This highlights the importance of returning to the same sites year after year to record the traces revealed. Often decades are needed to record a complete site, but one can never be certain that all the features present have revealed themselves, and it may never be possible to predict when any new features might appear (Wilson 1978, 46-49; Hampton 1975, 118).

Similarly, at any one time there are usually only a very few sites present in any area that are revealed by crop marks. This is the case even in areas known to contain high concentrations of sites, such as on the river gravels of southern England. On the Thames river gravels, for example, under exceptional circumstances, and in very good seasons conducive to crop mark formation, there may be as many as one in every three fields known to contain archaeological remains producing crop marks (Wilson 1975, 59). This suggests that more than just a large SMD is necessary for archaeological crop marks to appear. If this were the only factor, one would expect all of the crop marks in a given area to be visible under these conditions. One explanation for the differential rates of development and appearance from field to field in any one year is local variations in soil depth and moisture content (Riley 1979, 32).

Above all, it is important not to lose sight of the fact that there *are* underlying differences below a crop mark, because there are disturbances to the soil profile caused by humans in the form of an archaeological site. Most workers seem to generalise about soil properties and drainage and climatic conditions, at the expense of noting that there usually are actual differences present that can be seen during excavation, and which comprise coherent structures, features and activity areas. Unlike 'natural' crop marks, which are created as a result of geological and geomorphological events, with non-anthropogenic infilling and

burial, archaeological crop marks represent a record of the human activity that took place at each site.

In this way, archaeological crop marks represent a record, albeit incomplete, of the deliberate alteration of an area. It is these remains that lie below crop marks and not just inexplicable changes in the water holding capacity of the soils there. There are ditches, pits, building foundations, midden deposits, hearths, animal holding areas and more, all of which have associated with them distinctive, recognisable archaeological materials. Examples of the way that crop marks have been related to actual relict features include those Iron Age remains excavated at Fisherwick, in the Midlands (Smith 1979, 19-37), the pits defining a Neolithic enclosure at Littleour, Perthshire, and also famously at Mucking (Barclay and Maxwell, 1998; Fowler 1975, 157; Miles 1983). Again, this suggests that there are likely to be more differences in the materials underlying archaeological crop marks than simple changes in water content. Riley comes closest to acknowledging this when he discusses differential rates of development of crop marks from an aerial photographers view (1979, 32).

So, despite much qualitative evidence and description, there are still no definitive answers as to why crop marks do appear, and it is highly likely that there is no simple answer to this complex question. The occurrence of geological and other natural crop marks would tend to undermine the case for an anthropogenic factor, but as the preceding discussion indicates, the latter tend to show, and indeed are often identified by, a crisper appearance. In addition to this, and perhaps more importantly, the case has been made that even parts of certain sites lying in the same field and comprising part of the same crop mark complex may not necessarily become visible when the critical SMD has been reached in that field. At Monktonhall, excavations of a crop mark site comprising a cursus monument and a Roman temporary camp confirmed that the aerial record was a relatively fair, if simplified, indication of their form. The investigation also revealed a series of very large pits, tentatively dated to the Bronze Age, which traversed the excavated area. Despite their size, there were no indications of their presence at all in the crop marks recorded at the site. This is attributed to the depth of soil cover and to the amorphous character of the features (Prof Bill Hanson pers comm; Hanson 2002), although neither factor is an entirely satisfactory explanation for the absence of differential growth above the pits. This all gives credence to the statement that:

“.... it has to be firmly understood that knowledge of the factors that produce crop marks is still very deficient and every crop mark is an exception to any single explanation.

(Pickering 1980, 51)

It is clear that there is much work to be done to reach a better understanding of the way in which crop marks appear over archaeological sites. Miles (1983, 74-84) reports on an in-depth examination of a crop mark complex at Claydon Pike in the Thames Valley. This involved a programme of aerial reconnaissance and examination of the photographic evidence, fieldwalking, geophysical survey, test-pitting and finally carefully directed excavation. The two-fold objectives of this project were to examine a series of settlement types common to the Thames Valley and thus increase the level of understanding of the larger area of the Thames gravels. More importantly for our present purposes, the project attempted to glean more information about the reasons why the crop marks appear, and the factors governing the visibility of the underlying features and correlations between ground-based and aerial information. Despite the systematic use of aerial reconnaissance for archaeology since the 1920's, there are still very few published accounts that examine the physical basis of crop mark formation in this way (Scollar *et al* 1990, 26). Part of the problem lays in the fact that information that could be used to learn more about this aspect of aerial archaeology, and the same could be said for geophysical survey responses, is seldom published in excavation reports in a way that links the results of remote sensing and invasive investigation. Such information would include the depth of topsoil, the size of the features that do or do not illicit responses and the nature of their fills (Miles 1983; Riley 1979, 28-32; 1987, 95-8). Combined excavation and aerial transcription plans, ideally incorporating any geophysical results are what is required (see for example Hampton 1983, 109-122), and are easily obtainable with the increasing moves towards digitised and GIS-based results presentation (see Chapter 5). Nevertheless, it is still unusual to see rectified plans of aerial photographs or geophysical survey plots reproduced in published site reports, authors plumping instead for the more aesthetically pleasing photographs of excavated features and site plans. It was suggested (Fowler 1975) that aerial photography and non-invasive fieldwork would in future be the mainstay of archaeological investigation, and this is now largely true if one considers the vast number of sites recorded compared to the small proportion excavated. This is the basis for Riley's call (1979, 28-32) for more information and for a better knowledge of

the properties of the media underlying the crop marks, which is essential for the advance of this non-invasive approach to archaeology

Turning from the general to the specific, the four factors identified as significant for crop mark formation: water, soil physical properties, soil chemistry and crop plant growth responses, are now considered in turn.

2.4.1 Water

Allen suggests that the differential growth seen in archaeological crop marks is due to “some subsoil disturbance which has affected (beneficially or adversely) the fertility or humidity of the soil” (1984, 43). This section concentrates on the part played by moisture differences in the formation of crop marks, although Allen’s statement also alludes to the effect of nutrient status, which is considered separately below. Soil moisture levels are, of course, dependent on several related factors (Table 2.2), illustrating once again the complicated nature of the interactions involved in these systems. The majority of researchers (Scollar *et al* 1990; Jones and Evans 1975b) attribute the formation of crop markings to the differential water-holding capacities caused by subsurface changes in soil properties due to the presence of archaeological features. This view is held by, for example, Maxwell (1978, 38, 40), who, as discussed above, recognised the increased productivity when flying in very dry seasons as indicated by the higher number of sites recorded.

At its simplest, a change in the weather from dry to rainy has been shown to obscure the markings that appear in grass due to parching after one night of rain. Grass is a notoriously poor medium for crop mark appearance, perhaps due in part to this observed rapid response to changing climatic conditions, although this is at odds with the earlier definition of parch marks as comprising areas where plant death has occurred. Perhaps there again needs to be a distinction between degrees of parching in grass, with death being the most extreme, and recovery, overnight or otherwise, lying towards the other end of the parching spectrum. It has been noted by some, however, that one rainy night does not make any significant differences to the visibility of marks in cereal crops (Allen 1984, 75), and by others that crop marks disappear in cereals in as little as a day following heavy rain (Wilson 1975, 59), again suggesting different degrees of moisture stress. The paucity of crop marks in grass is almost certainly a function of its root system, which is

very extensive compared to cereals (D P Moss pers comm), but unlike the deeply rooting cereals develops close to the ground surface. This would render marks appearing in grass much more transient and difficult to capture on film, a fact confirmed by M Brown (pers comm) who indicates that parch marks in grass do tend to vanish swiftly. Allen comments on the general trend for grass to show crop marks poorly. On the contrary, when conditions are right they can be excellent, for example at Inchtuthill in Perthshire where the traces of construction trenches of timber buildings within the Roman legionary fortress are visible in parkland in very dry summers (Pitts and St Joseph 1985, 253-5). Crop mark appearance has been described as a gradual coming into focus of the patterns as the difference between the archaeological features and the rest of the undisturbed soil become more marked. The definition of the crop marks may not be best developed for several weeks after their first appearance.

Table 2.2: Factors that Influence Soil Moisture Levels (Jones & Evans in Wilson 1975)

<i>Factor</i>	<i>Reference</i>
Precipitation	Jones & Evans in Wilson 1975
Evapo-transpiration	Jones & Evans in Wilson 1975
Temperature	Scollar <i>et al</i> 1990; Allen 1984, 75
Growth stage that the crop has reached	Wilson 1978, 47
Farming practices	Scollar <i>et al</i> 1990
Irrigation and Drainage	
Soil structure and texture	Jones and Evans 1975
Soil depth	Jones and Evans 1975
The water-holding capacity of the soil	Jones & Evans 1975; Scollar <i>et al</i> 1990, 58
The availability of ground water	Jones & Evans 1975

Modern farming practices such as deep ploughing and fertiliser applications, especially nitrogen-based fertilisers, tend to even out any variations in the top 50 cm of soil leaving only differences in water balance to account for the appearance of crop marks. However, according to certain workers, for a given microclimatic region, no matter what soil types are present, there is little difference in available water content in the upper 50 cm of the soil horizon (Scollar *et al* 1990, 74; Jones and Evans 1974, 3). These views together effectively remove all of the proposed causes of archaeological crop marks and suggest that the affected plants are able to draw on reserves held deeper than those in the

cultivated zone of the topsoil, hence the significance of deeply rooting cereals. If the assertions are true, it would seem that the differences in crop growth are the direct result of differences in properties within the archaeological features themselves. However, the assertion that most soils, regardless of structure and composition, tend to have a similar moisture holding capacity in the top 50 cm, with the largest volume of water held in the surface horizon is disputed by Moss (pers comm). She comments that complex systems such as soil moisture content cannot even be agreed upon between soil scientists. Table 2.3 indicates the variable nature of moisture holding capacity between different soil types (D P Moss, pers comm). Whilst most agricultural topsoils do appear relatively homogeneous in colour and texture, there are exceptions to this of which archaeological soil marks represent a clear example. Not all these differences can be ascribed to moisture variations, but rather to soil textural differences, as for example, in the dark, humic lines of the soil that represent the crop mark section of the Cleaven Dyke's ditches in Perthshire (Barclay and Maxwell, 1998). Second, and in direct contrast to sites that produce soil marks, it is often the case that the archaeology which is responsible for the appearance of the crop mark lies at a minimum depth of around 50 cm below the ground surface, perhaps because the plough has eradicated evidence of the site in the plough zone.

This tends to confirm Jones and Evans' assertions about the homogeneous nature of the topsoil, and suggests that the differences responsible for crop mark development lie within the levels that contain archaeology, rather than being associated with topsoil properties. Alternatively, several studies have shown that materials ploughed up from archaeological layers and incorporated into the plough soil do not tend to travel far from the source. This applies not only to lithics and sherds (Clark 1983, 128; Gingell and Schadla-Hall 1980) but also to magnetic and soil phosphate enhancement derived from anthropogenic activity (Clark 1983, 129). This suggests that any chemical differences derived from underlying remains may be introduced into the ploughsoil and retained locally, rendering it available for uptake by a growing crop. This suggestion is strengthened by the observed concealing effect that nitrogen fertilisers have on crop mark sites, suggesting that there may be chemical variations in the soil whose effects are reduced by the addition of inorganic fertilisers. It must also be borne in mind that different soil textural types have varying abilities to hold chemical substances and make them available to crop plants. This is likely to explain why additional fertilisers do not

completely remove the traces of crop marks, and is further evidence of the role of soil texture in crop mark formation. This is discussed further in Section 2.4.4.

Table 2.3: Moisture Content in Topsoils and Subsoils of Varying Texture, Measured in mm of Water

Soil Texture Type	Topsoil: Moisture Content (mm)	Subsoil: Moisture Content (mm)
Sand	45	60
Loamy Sand	50	80
Sandy Loam	60	110
Fine Sandy Loam	90	150
Sandy Silt Loam	105	200
Silt Loam	115	200
Silty Clay Loam	100	140
Sandy Clay Loam	75	110
Clay Loam	115	180
Sandy Clay	110	190
Silty Clay	145	240
Clay	90	150
Organic ⁺	125	200
Peaty ⁺⁺	135	240
Peat ⁺⁺⁺	150	240
Chalk	90	150
Rock (Not Chalk)	45	60

6-20% Organic Matter ⁺⁺20-50% Organic Matter ⁺⁺⁺>50% Organic Matter
(Information from D P Moss)

Soil Moisture Stress

The unpredictable nature of crop mark site appearance, discussed earlier, can be explained in terms of soil moisture availability and the stage of growth that the crop plants have reached (Wilson 1978, 47). Significantly, although dry years are often quoted as being those in which the finest crop marks are seen and in which the chances of seeing new sites or additional features for the first time are increased, this identification of new

features is not always linked to dry years (Wilson 1978, 48). Jones and Evans (1975) note that crop marks occur mainly in shallow, loamy soils with rooting depths between 30-60 cm (see Section 3.3.3). The diverse causes are thought to result from the interaction of SMD (discussed below) with other soil characteristics, notably structure and texture. The differential exhaustion of available soil moisture in periods of high potential SMD accounts for the most distinct marks. These are occasionally obscured when short periods of Soil Moisture Surplus (SMS) alter differential growth patterns. SMD is used as an indicator of the likelihood of crop marks developing over archaeological sites. The SMD is a cumulative figure calculated by taking the monthly precipitation for an area, and deducting from it the water lost through evaporation and transpiration (evapotranspiration) (Scollar *et al* 1990; Jones and Evans 1975, 7). If there is more water entering the system than there is removed, there is said to be a Soil Moisture Surplus (SMS). If the outputs exceed the precipitation, then there is an SMD. The terms and equations commonly used to describe water content in soils are summarised in Table 2.4 below.

The rainfall maps used to calculate SMD are not a measure of the water actually available to the growing plants. This is defined by the Available Water Content (AWC) (for definitions of all of these terms see Table 2.4). Several workers discuss field capacity (FC) and permanent wilting point (PWP) (White 1987, 91; Scollar 1990, 64; Jones and Evans 1975). For most plants the PWP is reached at a hydrostatic pressure of around 0.05 bars (-1500 Joules per kilogram (J/kg)). The hydrostatic pressure of the water held in the soil pore spaces increases approaching PWP because the extraction of the increasingly small volume of water from the pore spaces becomes progressively harder. This is due to the cohesive forces associated with the increasing contact angle of the water meniscus with the pore walls, requiring a higher suction to release the last available water (White 1987, 80-95). These values are not precise, with both being dependent upon individual soil and crop properties, particularly soil particle size distribution, and the ability of the individual crop to adapt to survival through an SMD. As the water available moves below FC, and towards PWP, an SMD develops. Growing plants start to draw on stored water available to them in the soil until PWP is reached (Jones and Evans 1975, 3).

As usual, this is not as simple a process as it would first appear. First, not all species wilt rapidly when water supply is restricted. Some plants are adapted to stop growing but to continue to transpire at much reduced rates in response to moisture stress (Jones and

Evans 1975, 3; White 1987, 91). In addition, the effects of moisture stress in cereal crops are dependent on the stage of growth that the plants have reached when they experience it (Riley 1996, 27). For example, they require much more water in the earlier growth stages before the head appears, than after heading. Finally, the plants may avoid the effects of drought by drawing water from the groundwater table if the roots can reach to between 60-90 cm (Riley 1987), or by maturing before water stress becomes limiting. This helps to explain the importance to crop mark formation of the weather in spring and early summer discussed earlier, which is known to affect the clarity of summer crop marks (W S Hanson, M Brown, pers comm)

The actual SMD is difficult to calculate depending as it does on such variables as the area of soil covered by the crop, which changes as the plants mature. Therefore, the Potential SMD (PSMD) is usually calculated. This is a cumulative calculation, based on previous SMD or SMS for the area. As such the figure can hide more subtle trends in the water balance. For example, a few very wet days in the middle of a dry spell would not allow a surplus to be shown amid the increasing deficit (Jones 1979a; Scollar *et al* 1990, 59-63), but may nonetheless inhibit crop mark formation. This figure is, however, a useful indicator of the onset of conditions likely to produce crop marks.

Generally, commencement of crop mark appearance is rare until the PSMD in an area reaches a minimum of 50 mm. Jones and Evans have noted the appearance of natural crop marks, marking changes in pedological conditions, at PSMDs of 100 mm or more, suggesting different factors may be involved in the formation of archaeological crop marks (1975; Scollar *et al* 1990, 74). However, the development of “very extensive crop marks” in Nottinghamshire and Yorkshire corresponded to an SMD of around 100 mm (Riley 1987, 38; 1980). This suggests that the figure of 50 mm PSMD is a minimum only, varying with local soil and drainage conditions, as would be expected, and highlights one of the disadvantages of the SMD model. Amongst other factors, it fails to take into account the effects of drainage and temperature. Drainage, either artificially drained fields or natural as encountered in freely draining sandy soils and on sloping land, increases the likelihood of crop marks appearing at lower calculated SMDs (Scollar *et al* 1990, 65). Evapotranspiration and the length of the growing season are affected by temperature, which is not explicitly included in the PSMD calculations, although it is implicitly incorporated as evapotranspiration is included and the calculations are cumulative (Jones and Evans 1975).

Table 2.4: Soil Moisture Terms and Equations

Soil Moisture Balance = monthly precipitation – evapotranspiration.

Soil Moisture Surplus: SMS. More water put into the system than taken out.

Soil Moisture Deficit: SMD. More water removed from the system than put into it.

Available water content: AWC or A_v .

The amount of water in a soil available for plant growth. Usually measured as the volume of water held at field capacity, minus that remaining at permanent wilting point (ie tightly held in the pores and unavailable to plants)

Field Capacity: FC. At FC:

- All pore spaces smaller than 30 μm are full (μm = micrometers = 1×10^{-6} cm)
- Drainage is complete and ceases
- The hydrostatic pressure of pore water is $c -10 \text{ J kg}^{-1}$
- Crop growth is at an optimum
- FC defines the upper limit of the AWC

Permanent Wilting Point: PWP. At PWP:

- Plants lose their turgor and wilt
- The hydrostatic pressure in the pore spaces is $c -1500 \text{ J kg}^{-1}$
- PWP defines the lower limit of the AWC, when all freely available water is used.

FC \rightarrow water loss \rightarrow SMD \rightarrow water loss \rightarrow PWP
 \downarrow

Plants begin to draw on available stored water in the soil.

Potential soil moisture deficit: PSMD:

A cumulative calculation based on the previous SMD/SMS for an area.

$\text{PSMD} - A_v$ = degree of moisture stress suffered by growing crop.

Crop Adjusted PSMD CPSMD:

Describes the effects of evapotranspiration on an immature canopy, ie one that does not completely cover the ground surface. Until cover is complete, the PSMD is reduced by 1/3.

When rainfall again exceeds evapotranspiration and continues long enough for the SMD to turn into an SMS, summer crop marks tend to disappear. This can occur when stimulation of tillering in crops, induced by heavy rain showers, alters the pattern of differential growth. Tillering is a function of cumulative temperature reached over the period of the growing season (T_{sum}) and nitrogen supply (the more available nitrogen, the more tillers produced) (D P Moss pers comm). The fresh growth produced decreases

tonal differences across a field, and increased foliage density of the whole crop disguises positive crop marks (Jones and Evans 1975, 8).

There is little information on the effects of an SMS compared to the effects of an SMD, not least because of reduced reconnaissance in wet weather, but crop marks have been recorded under these conditions. They tend to develop in shallow soils, including those with an impermeable layer or pan within 60 cm of the ground surface. They are thought to be the result of restricted root growth due to excess water (Jones and Evans 1975, 8-9). Excessive water in the root zone may result in anaerobic soil conditions, which adversely affect the whole plant. Reduced growth results producing negative crop marks due to inhibition of nutrient uptake by the plant roots, which in turn leads to reduced respiration and photosynthesis (Jones and Evans 1975, 9). Crop marks produced as a response to SMS conditions usually appear following a wet May, and often the appearance of negative crop marks are enhanced by the invasion of weeds where the crop plants are failing. Jones and Evans cite crop marks at six UK sites, photographed when the PSMD was less than 40 mm, as probably being due to excess soil moisture (Jones and Evans 1975, 9). This situation is examined empirically, along with responses of barley to conditions of SMS, SMD and FC, in Chapter 6. Table 2.4 above summarises the terms used in describing soil moisture conditions.

An extreme example of crop marks caused by a local SMS is recorded on an aerial photograph from the CUCAP collection, which appears to reveal a series of round barrows. The marks are actually due to irrigation from inaccurately adjusted rotary sprinklers (Wilson 1975, 68). As such these are crop marks caused solely by water differences, although in this case they are not due to underlying archaeological features or changes in the soil profile, but merely an excessive amount of water applied to the area.

Experimental Work Associated with Archaeological Crop Marks

Penman (1948) ran a series of long-term experiments at Rothamstead Soil Research Station, Harpenden, Cambridgeshire, which looked at irrigation. The results suggested that the growth of both grass and arable crops was limited at a PSMD of 50 mm. In many soils this corresponds to the available water in the top 30-40 cm of soil (Jones and Evans 1975). This is the average depth of rooting and of the concentration of plant nutrients in soil, and as such is the zone that is most important for plant growth. The experimental

work led to the conclusion that, while the potential growth of a crop is determined by climate, the actual growth is determined by soil fertility, and that this growth is always less than the potential figure based on climate alone (Penman 1948). In other words, when considering plant growth it matters less what the predictions of growing season, PSMD and other climatic variables are, and more that there are sufficient nutrients in the soil and within reach of the roots.

Jones and Evans conducted a series of experiments to examine crop marks induced by soil moisture stress (1975, 7). They chose 45 sites on mainland Britain where crop marks had been recorded and estimated the PSMD for each location. At all but six of the sites, there were no visible crop marks at a PSMD of 40 mm or less. For those sites that appeared every year, the critical PSMD was 50-65 mm. However, as Figure 2.1 shows, the range of PSMDs at which crop marks could be photographed was wide, and varied between 40 and 295 mm.

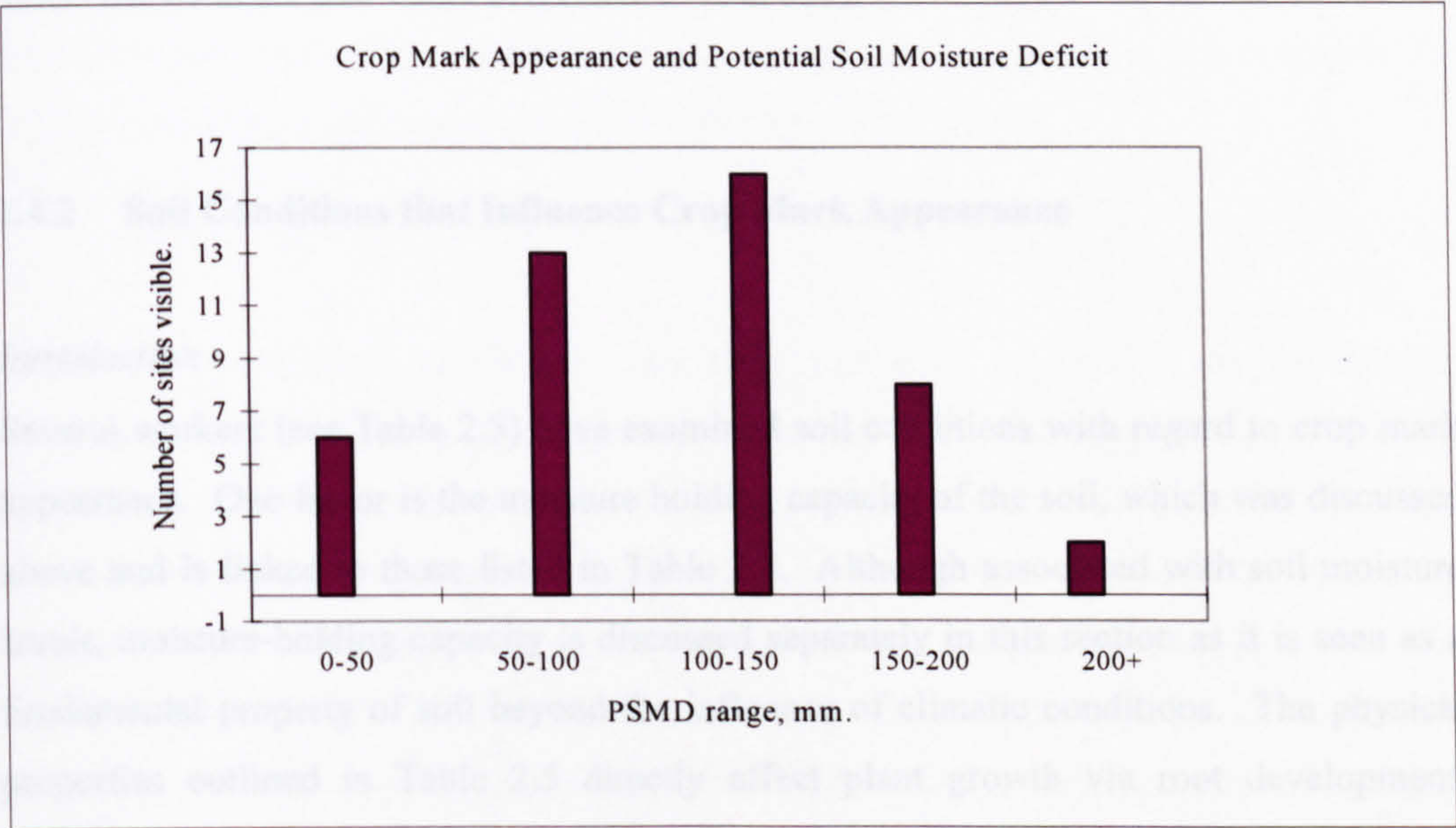


Figure 2.1:

The number of sites recorded photographically from the 45 studied, over five PSMD ranges.
(From Jones and Evans 1975).

At some sites the crop marks became faint at higher PSMDs, thus reducing the number visible. This was thought to be due to the whole crop, including the plants in areas of deeper soil over fossil ice wedges or infilled ditches, beginning to experience moisture stress (Jones and Evans 1975, 7).

In a precursor to this study, crop marks appearing at the site of an enclosed Iron Age farmstead at Fisherwick, Staffordshire were the subject of an in-depth investigation (Jones 1979a, 663). Estimates of available water were made for the undisturbed soil profile adjacent to the enclosure ditch and for the ditch itself. The effective rooting depth of the undisturbed soil was estimated to be 45 cm, and the A_v , 80 mm. In the enclosure ditch the effective rooting depth extended to 165 cm, with an estimated A_v of at least 200 mm. With barley roots estimated to penetrate down to around 100 cm in an average year, this gave an effective A_v in the ditch of about 140 mm. This meant that as PSMDs developed during the growing season to the point where moisture supplies in the natural soil were exhausted, the deeper fills of the enclosure ditch still contained sufficient water for the plants over the ditches to continue to grow. Crop mark appearance was correlated with the development of a water deficit in the natural soils, based on the calculation of A_v minus the CPSMD (see Table 2.4; Jones 1979a, 666).

2.4.2 Soil Conditions that Influence Crop Mark Appearance

Introduction

Several workers (see Table 2.5) have examined soil conditions with regard to crop mark appearance. One factor is the moisture holding capacity of the soil, which was discussed above and is linked to those listed in Table 2.5. Although associated with soil moisture levels, moisture-holding capacity is discussed separately in this section as it is seen as a fundamental property of soil beyond the influence of climatic conditions. The physical properties outlined in Table 2.5 directly affect plant growth via root development, because they are responsible for the properties of the rooting medium.

Soil structure and texture determine the way in which water is held in individual soil types, and are largely responsible for the different responses in plants when dry weather conditions prevail. Coarse sandy soils, for example, readily release all stored available water because it is held in the large pores, or void spaces, within the soil. Thus, plants in

sandy soils grow rapidly until all of this available water has been transpired, then experience sudden and severe deficit conditions, which persist until the soil is re-wetted, but often result in plant death. Conversely clay soils have a higher number of much finer pore spaces and hold water much more tightly because the cohesive forces within the pores make it progressively harder to extract the diminishing amounts of water held at progressively higher tensions (see Section 2.4.2). This causes a much more gradual reduction in growth rate than that seen in sandy soil, until the PWP is reached. Consequently plants growing on clay soils are capable of accumulating dry matter (in the form of increasing biomass) for longer than those on sandy soils once an SMD develops. Jones and Evans cite this as the reason for the sudden appearance of crop marks on sandy soils compared with their gradual appearance, if at all, over clays (1975; Riley 1987, 35-7). The particle size distribution within a soil dictates the size of its pore spaces as it affects the way in which the grains pack. Smaller grain size allows closer packing of the grains and so smaller spaces between them, but with more pore spaces per unit volume than there would be in a soil with larger grains. As grain size increases there are fewer points of contact between the grains and they are unable to pack together as closely. Consequently the inter-grain spaces increase in size. Because both grain size and pore spaces are larger, there are comparatively fewer of both per unit volume. This explains why there are much greater water reserves per unit volume held in a fine silty soil, for example, than there are in a coarse sandy soil (Riley 1987, 35-8).

Textural and structural conditions have been shown in practice to vary noticeably between soils taken from archaeological features and from their surroundings (Scollar *et al* 1990). This has also been noted with regard to the formation of certain soil marks, which also have the potential to produce crop marks if crops are sown over them, and may allow moisture marks to be seen after rain due to the differential drying of the bare soils (Scollar *et al* 1990, 46). This difference in soil texture is illustrated with an example discussed further below, in which Romano-British drainage ditches are noted by their humus-rich ditch fills amid the fine, silty Fenland soils (Riley 1987, 35). The textural differences noted allow the continued growth of plants above the ditch features, even though the rest of the field may have reached an SMD of 50 mm or more. The differential water balance in these features is a function of the textural and structural differences, notably the increased humus content (Riley 1987, 56). However, there is doubt as to whether the textural differences are strictly that, a difference in particle size

distribution, or whether there is better mixing of the particle sizes in the archaeological soils throughout their depth. This is discussed below.

Table 2.5: Factors that Affect the Moisture Holding Capacity of Soils

<i>Soil Texture</i>	
Particle size distribution.	White 1987, 10; Jones and Evans 1975, 3.
<i>Soil Structure</i>	
Particle characteristics.	White 1987, 46-9.
Particle aggregation.	White 1987, 46-9.
Proportion of void spaces.	White 1987, 46-9.
Relationship of void spaces.	White 1987, 46-9.
<i>Soil Depth</i>	
	Wilson 1975; Jones and Evans 1975, 7; Riley 1996, 31; 1983, 59-72
<i>Physical Properties</i>	
Soil composition	
Porosity	
Consistence	
Degree of compaction	
Stoniness	
Mineral fraction of the soil	Jones and Evans 1975
Kind and amount of organic matter	Jones and Evans 1975
<i>Subsoil characteristics</i>	
Drift geology	Riley 1983, 59-72
Solid geology	Riley 1983, 59-72; D P Moss pers comm

Soil Particle Size

Moisture differences in buried archaeological features that produce crop marks may be partly the result of differences in soil grain size. The particle size range influences the pore size and volume, as discussed, and it has been established that this affects not only water-holding capacity (Scollar 1990, 56; Jones and Evans 1995), but also the retention of nutrients (White 1987, 14). It has been suggested that archaeological features contain a larger number of fine grain sizes (Strunk-Lichtenberg 1965, 175-202). If this is the case, in addition to influencing the water-holding properties, it will also affect the pH of the environment, because fine grains in soils allow hydrogen ions to combine with other ions present in different ways compared with those soils with larger grain size distributions. In addition to this, a higher distribution of fine grain sizes tends to be associated with a larger humic content, which also affects pH (Scollar 1990, 57). However, it has been

suggested that the finer grain sizes are not present in particularly greater proportions in archaeological features compared to natural soils. Instead the finer particle sizes within the features are more thoroughly distributed and mixed throughout the profile.

Soil Depth

The depth of a soil plays a significant part in the appearance of crop marks (Wilson 1975, 59; Jones and Evans 1975; Riley 1996). The increased depth of soil alone in an archaeological feature cut into subsoil of gravel is sufficient to constitute an important water reserve, as discussed above. A shallow depth of soil has been suggested to be a more significant factor than soil texture in crop mark formation (Jones and Evans 1975, 10). Where a thin soil cover is present, less water can be held in reserve than if the soil is thicker (Riley 1987, 35), and this is certain to hold true for nutrient reserves too. This is the traditional explanation for negative crop marks in barley and, more significantly, the cause of parch marks in grass. Deeper soils have been observed to be less likely to produce crop marks, which are very common in sandy or loamy soils measuring around 30 cm in depth above gravel or limestone, and very rare in places where soil depth reaches 1.0 m. Where topsoil is greater than 50 cm in depth, buried ditches have been observed to cause a less pronounced crop response, decreasing further as soil depths reach 1 m (Riley 1996, 31).

A second aspect of soil depth relates to the occurrence of an impenetrable layer. Such a layer below the ground surface can be caused by farm machinery, animals regularly crossing an area of land, an iron or manganese pan developed in response to drainage conditions, or of course the presence of buried archaeological remains. For the former two, depth to the compacted layer is a function of the plasticity of the soil and the weight of the traffic, with the depth of compaction increasing in proportion to traffic weight. These forms of compaction are regularly detected during resistivity survey, producing either a high or low resistance anomaly depending respectively on whether the compaction is at the instrument's average detection depth, or whether it is deeper and thus impeding drainage. Iron and manganese pans can often be seen during the excavation of cut features as rusty or dark purple-black layers towards the base of the features. This leads to the concept of effective natural soil depth, which is defined as the depth of soil that can easily be exploited by plant roots (Jones 1979a). Compacted layers, pans and very stony or gravelly subsoils, which are moisture and nutrient poor, restrict root

penetration. Where known, the effective natural depth should be used in water balance calculations as this represents a more realistic value for the amount of water available to a crop.

Cereals are deep-rooted plants, which are affected considerably by differences in the depth of soil (Riley 1987, 29-30). The importance of the role of effective soil depth in root development can be demonstrated when fields that are apparently devoid of buried archaeological remains are deep ploughed, following which crop mark formation is often initiated (Agache 1975, 72). This suggests that exchange between buried features and plants is necessary for crop mark formation. It is not certain whether this is associated with water-holding capacity, or whether the nutrient reserves made available together with increased root penetration into the archaeological layers are responsible for the development of crop marks. Deep ploughing, whose main purpose is to bury weed seedlings and stubble, also stimulates the mineralization of soil organic matter, which allows nitrogen to become available to the crop. As it has been demonstrated to initiate crop mark formation, it is possible that the mechanism by which this occurs is associated with the supply of nutrients from the archaeological remains, thus implicating soil chemical differences in crop mark formation.

Soil Colour

Soil colour, a quantifiable character of soils, may influence the formation of crop marks, especially if these colour differences are related to changes in chemical composition and organic matter status. Jones and Evans (1982) discuss the use of Munsell soil colour charts for the examination of soil marks. Providing that the soil surface is reflecting light uniformly, commonly used red-sensitive panchromatic films will tend to show the more red colours (eg 10YR in Munsell notation) as lighter tones than the less red ones (eg 2.5YR). This is the case even if they are of the same value (an indication of the relative lightness of the red colour, with reference to black and white) and chroma (the strength or purity of the red colour).

Tonal contrasts vary with soil moisture content. For example, in shallow soils over chalk the contrasting tones of soil marks are greater at Soil Moisture Contents (SMCs) between 5-6%, compared with contrasts in the same soils at SMCs of 1-2% and 19-22%.

Spectroscopic examination of bare soils reveals that they usually show a four-peaked spectral range (Table 2.6), one in the near infrared, and the other three within the range that can be recorded on film (Scollar 1990, 38-9; although a dictionary definition of infrared is given as lying between the visible and microwave regions of the spectrum, i.e. approximately 0.75 to 1000 μm , with the near infrared spanning the portion 0.75 to 1.5 μm ; Walker 1991, 464).

It is probable that the iron compounds mentioned in Table 2.6 might be responsible for the magnetic anomalies that arise at many crop mark sites in the UCVLP surveys and also for the differential growth of the crop plants. If this correlation exists, the variations in soil colours may provide us with our first link between aerial images and magnetic survey results. This will be discussed in Chapter 6.

Table 2.6: Spectral Absorption Peaks of Compounds and Soils

<i>Absorption Band</i>	<i>Cause</i>
1.44-1.94 μm	Water
2.08-2.32 μm	Soil Moisture (high correlation)
0.9 μm (near infra-red)	Iron (ferric) oxide
1.0 μm	Ferrous iron compounds

Soils and Geology: Maps and Observations

Soil properties are often used as a basis for the prediction of crop mark appearance. For example the lighter and better-drained soils overlying geological terrains such as chalk, limestone, sand and gravel are identified as being most favourable for the appearance of crop marks. Heavy soils, such as those developed on marl and clay, are less favourable (Wilson 1979, 33).

Use has been made of soil maps in England and Wales, together with land capability maps, to identify arable areas prior to reconnaissance (Wilson 1979, 32-6). The land use capability maps were found to be more useful for these purposes than the soil maps, which were found to be too detailed for prediction of crop marks. This was highlighted by comparison of crop mark locations with mapped soil boundaries, which revealed crop marks continuing unaltered across the soil boundaries (Wilson 1979, 32-6). Land Use maps are based in part on the soil maps, however, so the information on soils is

incorporated implicitly into the predictive model. One problem with the soil maps is that they tend to be very small scale (1:1,000,000 in this case) and mapped boundaries can occasionally be somewhat artistically determined (D Moss pers comm). Work on the soils of the UCVLP area (see Chapter 4; Hanson and Sharpe in prep.) relative to crop mark appearance suggests that if soil types are grouped by their drainage properties, rather than examining the mapped individual units, there is better correlation between soil type and crop mark distribution

Maps of solid geology were not found to be as helpful, with the drift deposits tending to have more influence on the development and clarity of crop marks than the underlying bedrock (Wilson 1979, 32-6). Riley, however, was able to correlate the incidence of crop marks in Northern and Southern England with not only soils but also solid and drift geology and arable crop type (1983).

The use of maps to identify areas that in theory should be favourable for the appearance of crop marks raises the question of bias. Would this kind of directed reconnaissance increase the bias toward flying in areas known to be conducive to crop mark development, or conversely could it encourage less favourable areas to be identified and targeted during favourable years (Hanson and Macinnes 1991, 157)? We must not lose sight of the fact that we are looking for areas of earlier activity and habitation, which surely would not have been confined to certain geological or soil units, although one has to accept a possible bias in habitation choice too.

Crop marks appearing over the river gravels and terraces in Southern England are a well-known phenomenon and this is also the case for natural crop marks (Jones and Evans 1975). By comparison, as discussed earlier, notoriously unproductive areas include those underlain by Jurassic limestone, Keuper marl or other clayey parent materials, although recent examination of clay geologies in Bedfordshire suggest that this may be a mixture of habitation- and recording-bias (Mills 2003, 12-19). There is less information on the influence of solid geology upon crop mark appearance in Scotland. In the Anglian region, Wilson suggests that all of the concentrations of crop marks can be related to solid and drift geologies, if the information from the two is combined. "Both the solid rock and the superficial deposits are important because they are the parent material for the soils in which crops grow, and it is really the soils with which we need to be concerned" (Wilson 1979, 34).

In an attempt to quantify the effects of soils and geology on crop mark formation, Jones and Evans (1975, 4-7) investigated sites at over twenty-six locations as far apart as Southwest Scotland, West Wales, East Anglia, the West Midlands and Lincolnshire. At each location, natural crop marks had been recorded on aerial photographs and the soils at each site were investigated. Gravels underlay twenty-three of the sites. The remaining three lay upon limestone, or sandstone and shale (Culm Measures). At twelve of the former sites there was a sharp subsoil change at around 30-40 cm to either rock or pan. The topsoils ranged from sandy clay-loam through to silty clay-loam, and included some peaty soils. The soil depths varied between 10 cm and 100 cm, with 17 sites having soil depths of 30-60 cm, and three of the sites having soils deeper than 60 cm (Figure 2.2).

At the same time, thirty-six archaeological sites were examined. All of these sites lay on riverine or glacial gravels, with a minimum soil depth of 15 cm. Most of the sites had a soil depth of less than 76 cm (except 2 sites), and of these, 28 had a soil depth of less than 61 cm. These sites were chosen to correspond with the soil depths of the sites revealing natural crop marks. Figure 2.2 shows the number of crop marks recorded relative to soil depth for both natural and archaeological features.

Soil depth can be seen to influence the appearance of both natural and archaeological crop marks, although the divisions of soil depth given in the report are not particularly specific. Further to this work, two fields in Cambridgeshire were the subjects of an investigation. The first field reveals ice wedge crop marks every year in Fordham soils with an average depth between 42-70 cm. The second field produced markings only once in ten years in Adventurers' series soils averaging 73-95 cm deep. Although the former soils are less extensive than the latter (23% of the photographed area, compared to 32% coverage by the Adventurers' series), crop markings cover 40% of the Fordham soils compared to a 7% cover on the Adventurers'.

The Adventurers' series comprise soils derived from reed and sedge peats, with subsoils predominantly comprising humified peat below the well-decomposed organic topsoils. Only the better-drained areas of these soils are cultivated, and tend to be in arable use. The Fordham series, by comparison, comprises usually waterlogged black humified peats and sandy loams with gleyed subsoils (Ragg *et al* 1984, 75-77). Unlike the Adventurers' soils, which tend to be stone-free throughout the profile, Fordham soils tend to have a significant stone content, which frequently increases with depth. Although the Fordham

soils tend to be predominantly under pasture, the land-use is determined mainly by the climatic conditions prevailing, and when improved, liming and fertiliser applications are essential to maintain soil condition (Ragg *et al* 1984, 333-5).

Finally, markings in an oat crop observed from the ground on 11.7.69 on a Huntingdonshire river terrace could not be seen in adjacent fields sown to wheat and barley. A difference of 15 cm in crop height within the crop mark was recorded. The pattern developed later that month in the adjacent fields. Auguring on a grid pattern showed that the average depth of the sandy clay-loam soils in the field of oats was 44 –70 cm, whereas in the barley field it was between 50-84 cm deep (Jones and Evans 1975, 7).

From these studies, Jones and Evans deduced that “Soil depth is more important in the formation of crop marks than particle size class” (Jones and Evans 1975, 7).

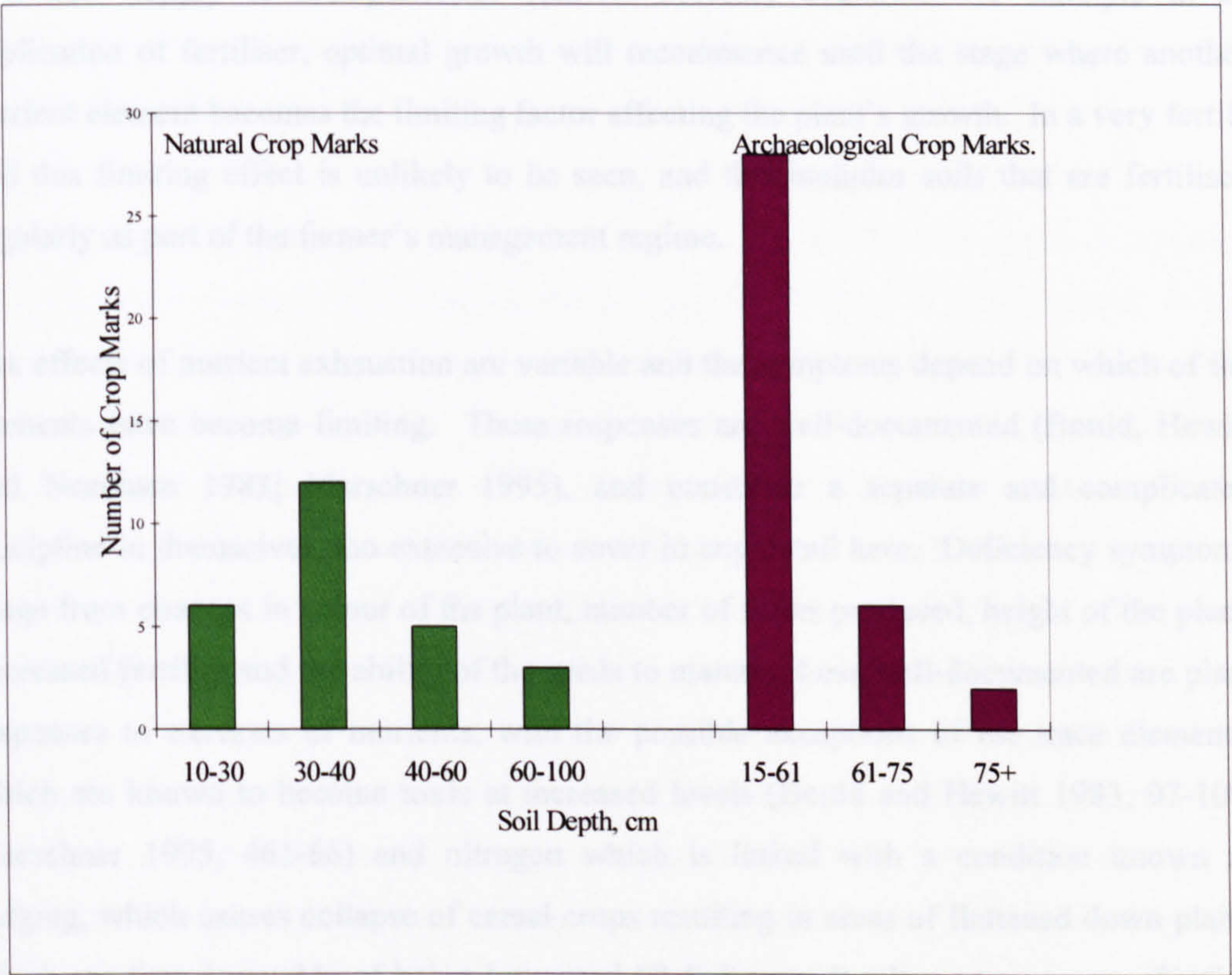


Figure 2.2:
Occurrence of natural and archaeological crop marks relative to depth of top soil.
(Based on Jones and Evans 1975).

2.4.3 Soil Chemistry and Nutrient Status

Introduction

A plant that is developing optimally has access to all of the nutrients necessary for growth at the required levels and in the correct forms for uptake. If there is an endless supply of available nutrients in the soil, so that none of them becomes depleted due to the growing plant's demand for them, the plant will continue to grow healthily and rapidly to maturity.

If one of the nutrients in the suite of those required for growth, whether major or minor, begins to be exhausted during the growth cycle, the whole growth process is affected, even though all of the other elements may still be present and available. This nutrient is then described as the limiting nutrient, as it prevents the continued optimal growth of the plant.

If a new supply of this particular element becomes available, for example in an application of fertiliser, optimal growth will recommence until the stage where another nutrient element becomes the limiting factor affecting the plant's growth. In a very fertile soil this limiting effect is unlikely to be seen, and this includes soils that are fertilised regularly as part of the farmer's management regime.

The effects of nutrient exhaustion are variable and the symptoms depend on which of the elements have become limiting. These responses are well-documented (Bould, Hewitt and Needham 1983; Marschner 1995), and constitute a separate and complicated discipline in themselves, too extensive to cover in any detail here. Deficiency symptoms range from changes in colour of the plant, number of tillers produced, height of the plant, decreased fertility and the ability of the seeds to mature. Less well-documented are plant responses to excesses of nutrients, with the possible exceptions of the trace elements, which are known to become toxic at increased levels (Bould and Hewitt 1983, 97-100; Marschner 1995, 461-66) and nitrogen which is linked with a condition known as lodging, which causes collapse of cereal crops resulting in areas of flattened down plants which are then incapable of being harvested (R Sylvester Bradley pers comm; Pinthus 1973; Berry et al 2004).

Two main factors introduced here that affect growth are the pH of the soil, and the elements present that are associated with plant growth. These are related as pH affects

the availability of nutrients to plants and is itself affected by elemental concentrations, soil moisture conditions and drainage. It continues to be the case that it is difficult to separate entirely the nutritional status and pH from the water holding capacity, textural and structural characteristics of the soil.

In most temperate soils, the largest and most available concentrations of plant nutrients reside in the top 30-40 cm. This corresponds to the major concentration of plant roots and helps to explain why exhaustion of available soil moisture to around 40 cm affects plant growth (Jones and Evans 1975, 4). The roots of many plants draw nourishment from depths which include the upper parts of many archaeological features (Scollar *et al* 1990, 50). The bulk of cereal roots tend to lie within the top 30 cm of the soil, and Russell (1971) has demonstrated that 90% of barley roots lie within this depth. In an average year the roots may extend down to around 1.0 m in the absence of barriers to this growth (Jones 1979a). Even deep rooting species, such as barley and those that develop deep tap roots, would experience limited growth, however, in times of SMD because at depth nutrient supplies may only be adequate to allow the plant to survive, but not to flourish (Russell 1971).

The literature is unclear as to whether this decrease in fertility with depth is constant across a field regardless of changes in the soil profile. If there is a differential, deeper areas of soil, including those filling archaeological cut features, would provide a more constant nutrient supply down to the base of the feature. This would then explain the more luxuriant growth over a cut feature in terms of an enhanced nutrient availability, because the larger volume of soil contained in the feature represents a larger pool of nutrients compared to the surrounding, shallower soil. An example with a twist from a natural crop mark suggests that this is the case. Crop marks have been observed in the Brecklands over heavily fissured chalk, the fissures infilled with predominantly sand and gravel. Positive marks were observed over the chalk because its porous nature allows it to act as a reservoir for overlying crops. Negative marks were seen over the 'deeper' soils of the fissures because they are too coarse to be able to hold as much water. The causes of the crop marks are thought to be two-fold, the moisture differences in the soils being the first. The second less obvious cause was found to be a sulphur deficiency commonly associated with shallow, alkaline soils, which by the time symptoms become visible it is too late to remedy. The two factors interacted to produce the differential growth patterns. Poor root development due to the sulphur deficiency resulted in

insufficient uptake of water by the roots, which also reduced nutrient uptake, resulting in poor growth of the plants comprising the negative crop marks (D Moss pers comm). So, although climate can be used as a measure of potential growth, as indicated earlier, experimental work shows that soil fertility is the main control over actual growth in reality (Jones and Evans 1975, 10).

A further indication of the role of nutrient status in crop mark formation is found on the deep, fertile *limon* plains of France (Agache 1975, 72), which were reputed to be unproductive in respect of crop marks. However, it was noted that crop marks could be seen in spring and early summer if the fields had not been heavily treated with fertilisers, suggesting that crop mark appearance here is related to nutrient levels in the soil. The features recorded were described as walls and pavements, suggesting that the crop marks were negative, but the explanation for their occurrence was in terms of nutrient status rather than SMD. Agache noted that a similar situation arose in Normandy when pasture fields were ploughed and converted to arable for the first time. Here the ability to see crop marks continued in the first years of arable cropping, until the farmer gave the first fertiliser applications (Agache 1975, 72). It has been suggested (Scollar *et al* 1990, 58) that modern applications of, particularly nitrogen, fertilisers even out nutritional differences in the top 50 cm of most soils, leaving water balance as the only variable that could cause crop marks. However, it is known that different soils retain nutrients differently, and that this is a function of texture. If a regular amount of a fertiliser is applied to a field which contains a humus-rich or silty ditch lying within a sandy loam or other contrasting soil, it is unlikely that both soil types will store and release the fertiliser in the same way and over the same length of time (White 1987, 14). If Scollar is correct in his assumption, this tends to suggest that soil moisture in fact plays no part at all in the formation of the crop marks observed by Agache in Normandy.

Chemical enhancement at sites, which may remain for some time after they have been completely destroyed by the plough, may be responsible for the so-called ghost crop mark sites. These sites produce crop marks, often seen with great clarity from the air and occasionally even from the ground, but upon excavation reveal no trace of features below ground. There are a number of examples of such sites from all around the British Isles. For example in Perthshire a ditch of a Roman marching camp at Inchtuthill identified from the air revealed no trace on excavation in the late 1970's. The ditch, thought to have been destroyed by the plough, is assumed to have caused some residual nutrient

enhancement, lasting until the material spread from the destroyed ditch had disbursed (D Evans pers comm). At Nailsea, North Somerset, a ring-ditch with associated fields appeared as a positive mark in grass, which on occasions could be seen from the ground in springtime. Despite its convincing appearance, there were no visible features or even soil changes below ground that could be found during excavation. All obvious agricultural effects having been ruled out, the crop marks were eventually attributed to the underlying geological conditions (Vince Russett pers comm). A general suggestion for the phenomenon is that the presence of buried features before plough destruction results in enhancement of soils and porous underlying solid geology in the vicinity of the feature. This provides the conditions under which crop marks still arise even after the total destruction of any physical evidence of the site. Colin Merrony has suggested a 'chemical signature' for similar crop marks appearing at a site at Goldthorpe, left by minerals leaching down through the ditches which continued to produce crop marks even after the ditches had been ploughed out (C Cumberpatch pers comm). Other examples of these ghostly crop marks come from Balneaves Cottage, a non-existent square barrow excavated by C J Russel White (NGR NO 605 497, Lunan Valley, NMRS no NO64NE 24, Mairi Davies pers comm; DES 1988, 26). Two sites near Winchester, excavated by Taylor, (1979) which were recorded as soil marks revealed virtually nothing in the chalk subsoil. Despite this, the site still produces evidence of positive crop marks (Rog Palmer pers comm). In Ireland there are numerous examples of crop marks being excavated between 1986 and 1999 that have no apparent underlying cause, most of which tend to be ring-ditches or similar sites (Maqqi Stiof pers comm).

An alternative explanation to residual soil chemistry changes that has been put forward in these cases is erosion of the soil profile containing the features. Excavations based on photographs originally taken in 1976 by Derrick Riley at Hunter Grange Farm near Rossington in South Yorkshire (Sydes 1991) revealed no features that could have been responsible for the crop marks. In this case the lack of features during the 1990-1991 excavations, some fourteen years after the crop marks had been recorded, was ascribed to the continuing erosion of the soil profile due to ploughing and weathering which had simply removed the layers containing the archaeology. The farmer was able to confirm this, commenting that the ability to see his house from an adjacent hill over the ridge on which the site lay had increased over the space of a decade. The erosion had effectively removed around 1 m of soil during this time (Chris Cumberpatch pers comm). However, Derrick Riley flew over the site during the excavation and found that despite this apparent

wholesale destruction, the crop marks were still visible around the excavation trenches “and at first he didn’t believe the ditches weren’t there” (Adrian Chadwick pers comm). Again, this evidence strongly suggests soil chemical differences for the crop marks.

A third possibility, despite the findings of Clark, Gingell and Schadla-Hall (see above) is that ploughing actually shifts the crop mark and displaces it from the associated buried features. This effect has been observed during an experiment undertaken by agricultural research workers at Rothamstead research station to determine the effects of poultry manure applications to sugar beet (D Moss pers comm). Following harvest of the beet and incorporation of the tops by ploughing, a wheat crop was sown directly over plots established when the beet was sown to chase the residual nitrogen value of the poultry manures. Air reconnaissance later revealed that when the wheat was sown, the new plots were not correctly located above the original positions. This was due to a systematic shift in the topsoil c 50 cm from its original position, which went unnoticed on the ground, resulting in an incorrect relocation of the grids. This example might suggest that inaccurate location of excavation trenches due to similar shifts may be responsible for some of the featureless crop marks, and suggests a further role for geophysical survey in crop mark site location. However, it has been noted that given the general problems of precise location of features based on oblique photos, any excavation trench planned would factor in a margin of error greater than that due to any shift caused by ploughing (Prof Bill Hanson pers comm). Additionally, location of features from plans made of crop marks using Aerial 4 for rectification purposes has commonly resulted in sub-metre accuracies (see Chapter 3), tending to rule out misplacement of excavation trenches as an explanation for lack of features. Furthermore, experimental work to determine the extent of plough-displacement of lithic scatters from their original undisturbed positions tends to confirm the limited degree to which archaeological remains of all descriptions are moved by agricultural disturbance (Boismier 1997), effectively also ruling this out as the cause of missing features.

pH

Wilson (1975, 59-69) indicates that pH is one of the contributory factors in crop mark formation. Factors known to affect soil pH include the composition of ground water and precipitation, which may be assumed to be reasonably constant over the area of a field. Chemical differences can also affect soil pH. As soil particle size distribution and hence

pore volume affect the water holding capacity of soil, this in turn must also affect its pH (Scollar *et al* 1990, 66). Ideally, soils that are in arable use should have a pH of around 6.5 (pH 6 for grassland), with liming undertaken as the standard method of attaining the correct soil pH. Increased acidification of soils is a consequence of acidic precipitation and dry deposition from the atmosphere, and (more significantly) from the addition of ammonium sulphate and now more commonly ammonium nitrate fertiliser. The effect of these inputs is to decrease the soil pH by the production of H^+ ions as nitrogen is transformed and taken up by plant roots (White 1987, 178). Other causes of acidification include the microbial oxidation of organic matter, producing acidic humic residues and increasing carbon dioxide, and thus carbonic acid levels within the soil. In soils formed on coal-bearing sedimentary rocks, such as those of the Midland Valley (see chapter 4), the oxidation of iron pyrites can give rise to acid sulphur soils (White 1987, 178).

Investigation of crop marks on Silt Fen soils and shallow chalk in East Anglia and Lincolnshire (Jones and Evans 1975) indicated that darker-toned soil marks over infilled ditches produced positive crop marks during the growing season. The explanation given for this was that the calcareous soils, measuring pH 7.5 or higher, inhibited bacterial oxidation of heavy ammonium fertiliser applications, preventing nitrites being further oxidised to nitrates which are then available for plant uptake (Figure 2.3). This inhibition is increased under cold temperature conditions, which accentuate the nitrogen-induced differences in spring as the lower-pH, darker ditch fills absorb more solar energy, becoming warmer than the surrounding lighter soils, thus allowing the Nitrogen Cycle to be completed. Nitrogen effects are further considered below.

Chemical Elements

In addition to the nutritive requirements of the plants there are environmental factors necessary for optimal growth. These include sufficient water, light and oxygen, appropriate soil and air temperatures, and a suitable rooting medium for the plant to develop in. As would be expected, these factors are inter-related, so that a suitable rooting medium, in this case cultivated agricultural soil, is prepared by ploughing and attention to soil structure to allow optimum crop growth. An open soil structure, which by nature contains adequate organic material, will ensure adequate water is held in the soil pore spaces. It will also allow the nutrient elements in the soil to be dissolved and transported to the roots and root hairs (the sites of active nutrient and water uptake) to

allow the plants to grow. Modern agricultural practices ensure that all of the factors required for optimum crop growth can be provided. Soil texture can be improved with the addition of bulky organic or green manures, nutrient status can be adjusted by the addition of fertilisers, poorly draining land can be rectified with field drains and, although not common in Scotland, irrigation can be applied to crops experiencing drought conditions. Despite all of this, the differences of crop plants growing above buried archaeological remains can still be detected, which leads to the question, what are the factors that cause this to happen?

Since the late nineteenth century work closely linked with the development of analytical chemistry has revealed that plants require to uptake certain elements to allow healthy development (Marschner 1995, 3-5; White 1987, 153). Today not only are the elements known, but also the concentrations in which different species of plants require them. Their concentrations in different soil types are also well-documented, as are the optimal levels required for successful cropping and the ability to control fertiliser regimes to maintain this optimum growth. Details of expected concentrations in plants, especially of those economic crops, including the cereals, are widely available, and this knowledge is used by the advisory agencies such as the Ministry of Agriculture, Fisheries and Food (MAFF) in England and the Scottish Agricultural College (SAC) in Scotland to assess nutrient availability in arable soils and advise growers on fertiliser applications and other cultural requirements that allow maximum yields to be attained.

This body of work recognises two groups of elements that plants require for growth. The groups are divided on the basis of the concentrations of the elements required, into the major or macronutrients, and the minor, trace or micronutrients. Three criteria were recognised in order to classify an element as essential to plant growth. First, in the absence of the element a plant would be unable to complete its life cycle. Second the element's function may not be replaced by another mineral element. Finally, the element must be directly involved in plant metabolism or required for a distinct metabolic step (Larcher 1995, 180). Table 2.7 lists the nutrient elements and indicates typical concentrations found in soils and in plant tissue. There is also a requirement for carbon (C), hydrogen (H) and oxygen (O), but these are supplied atmospherically from water (H₂O) and carbon dioxide (CO₂).

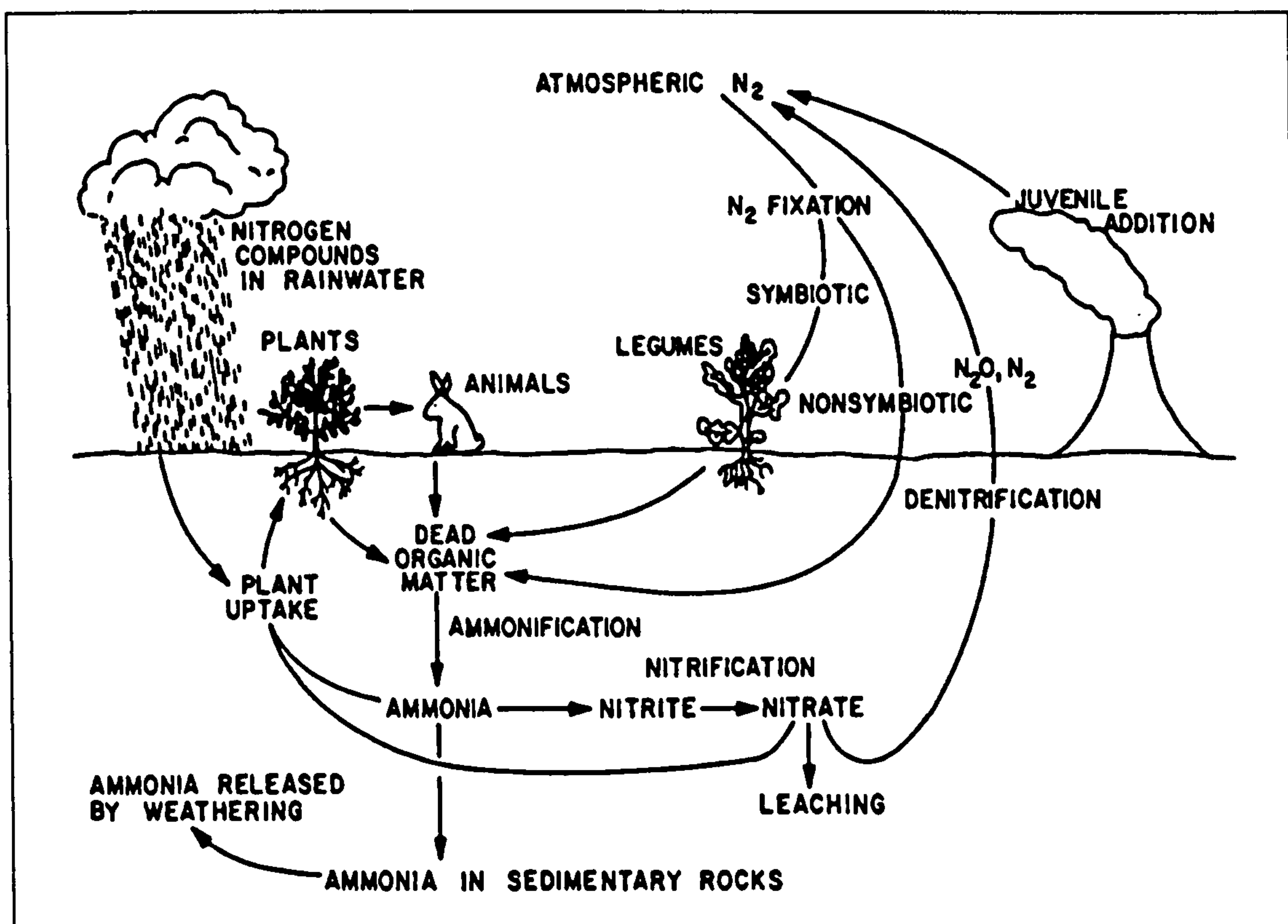


Figure 2.3:

The Nitrogen Cycle.
© Clark & Rosswall 1979.

The supply of these elements originates from the weathering of the underlying solid and drift geology parent materials, and from soil minerals. Maintenance of nutrient levels within the soil is cyclical, with removal by absorption at plant roots followed by translocation within the plant being compensated by a return of the nutrients to the soil in leaf litter (White 1987, 153). If the plants are cropped, as in arable systems, this cyclical process is interrupted and depletion of nutrients caused by removal of plant biomass must be compensated for by fertiliser applications. Maintenance of soil fertility represents a delicate balance between nutrient impoverishment and excess. The control of uptake of elements by plants from the soil is limited (Marschner 1995, 3), and dependent on the levels present in the soil and other factors including Available Water Content and root architecture (Marschner 1995, 500; D P Moss pers comm).

Table 2.7: Macro- and Micronutrient Concentrations in Soils and Plants

<i>Element</i>	<i>Symbol</i>	<i>Macro- /Micronutrient</i>	<i>Concentration in plants (g kg⁻¹)</i>	<i>Plant requirements (g kg⁻¹)</i>	<i>Concentration in soil (mean) (g kg⁻¹)</i>
Nitrogen	N	Macronutrient	12-75	15-25	2
Phosphorus	P	Macronutrient	0.1-10	1.5-3	0.8
Potassium	K	Macronutrient	1-70	5-20	14
Sulphur	S	Macronutrient	0.6-9	2-3	0.7
Calcium	Ca	Macronutrient	0.4-15	3-15	15
Magnesium	Mg	Macronutrient	0.7-9	1-3	5
Chlorine	Cl	Micronutrient	0.2-10	>0.1	<0.1
Iron	Fe	Micronutrient	0.002-0.7	c 0.1	40
Manganese	Mn	Micronutrient	0.003-1	0.03-0.05	1
Zinc	Zn	Micronutrient	0.001-0.4	0.01-0.05	0.09
Copper	Cu	Micronutrient	0.004-0.02	0.005-0.01	0.03
Boron	B	Micronutrient	0.008-0.2	0.01-0.04	0.02
Molybdenum	Mo	Micronutrient	up to 0.001	<0.0002	0.003
Nickel	Ni	Micronutrient	Up to 0.005	~0.001	0.05
Cobalt	Co	Micronutrient	Up to 0.005	-	0.008

From Larcher (1995, 178) and Marschner 1995(5)

In non-optimal situations a range of plant effects is seen. Starting with nutrient poor situations, where the plant displays visible nutrient deficiency symptoms (Boulds, Hewitt and Needham 1983), increasing supplies move the growth towards the optimum. If nutrient levels continue to increase, a stage is reached where one or more of the elements become toxic and growth is again adversely affected. If there is an increase in the supply of one of the elements, growth can also be affected due to other element supplies becoming limiting relative to this enhancement (Marschner 1995, 184-5), hence the balanced approach required for crop nutrition.

The chemical characteristics of plant nutrient elements determine how they are held in soil, which is also a function of soil texture and water content. For example, nitrogen tends to accumulate in the organic rich A horizon (topsoil) of a soil and its concentration declines gradually with depth. Sulphur and phosphorus display similar distributions,

although phosphorus content declines more rapidly with depth as the phosphate ion is quite immobile in soil (White 1987, 154). Although it has been established that the majority of cereal roots tend to occupy the top 30 cm of soil in a field, further work has demonstrated that the distribution of roots down a soil profile strongly correlates with the uptake of calcium by the crop (Marschner 1995, 519). Interestingly, from an archaeological prospective, this correlation also extends to phosphate uptake (Russel 1973). This provides a link between phosphate as an indicator of past activity in archaeological settings and crop mark formation, with positive growth associated with a well-developed root system. Furthermore, calcium along with nitrogen in forms which are available to plants can be easily leached from the surface zone and accumulate at depth under certain conditions (Jones and Evans 1975). Scollar *et al* however indicate that small chemical differences of calcium and phosphorus compounds particularly have not been proven experimentally to differ within archaeological features compared to the surrounding undisturbed soils (1990, 56).

The two elements, and nitrogen especially, are indicated as being responsible for the formation of natural and archaeological crop marks in certain cases (Jones and Evans 1975). As discussed earlier, Scollar *et al* (1990) tend to think that chemical differences due to the presence of archaeology are unlikely due to the length of time that the sites have been abandoned. The exception, they concede, may be remnants of walling, whose stone and mortar components could provide additional nutrients, such as calcium. This tends to be confirmed in work by Wilson *et al* (in prep). However, if this were the case, one might expect positive crop marks to develop over and around building remains due to increased root development aided by the calcium, but a negative crop mark is generally expected to indicate the presence of such remains in aerial archaeological circles. Indeed aerial photographs of crop marks of building remains usually betray evidence of insufficiency rather than additional support for growth. Unless this can be explained by misinterpretation, it may be due to an excess of calcium significantly affecting pH, resulting in crop marks being formed above such stone-constructed features not due simply to water stress, but also to lime-induced chlorosis. This is where iron in the soil becomes locked up in forms that are unavailable to plants due to high pHs produced by excess lime. Chlorosis causes yellowing of the leaves of the growing plants, and thus the negative crop marks that are commonly associated with masonry features. This example highlights the complicated and largely unexplored nature of crop mark formation. If negative crop marks are associated with chlorosis, this may represent a further link to soil

chemical differences and magnetic survey results. If the iron in areas containing calcium-rich remains such as mortared walls exists in a different form to that over the rest of the field it is likely that this chemical alteration of the iron minerals will affect the magnetic response locally, and may also play a part in the traditional high resistance responses recorded over building remains due to changed ionic composition.

Scollar *et al* (1990, 56-7) link textural and structural differences (soil grain size distribution and pore volume) to crop mark formation. They mention small chemical differences of calcium, phosphorus and nitrogen compounds in archaeological soils relative to their surroundings, but state that calcium and phosphorus have not been proven experimentally to differ in the archaeological features (although the success of phosphate sampling would contradict this assertion), and have no experimental data on the nitrogen compounds. They do, however, indicate that slight pH variations may be due to increased levels of humus, or to higher proportions of small grain sizes. Slight differences in acidity, due to a larger number of fine grains in a feature, capable of binding hydrogen ions, have been measured.

Nitrogen

Uptake of certain elements, especially nitrogen, has been shown to be the limiting factor in grass growth when an SMD greater than 50 mm develops. The preferential cultivation of grass in areas with PSMDs of less than c 50 mm, and on less free draining clay soils, are indicated as the main reason why grass crops tend to produce fewer crop marks (Jones and Evans 1975). Nitrogen is known to have significant effects on the growth patterns of other plants, such as lodging (excess) and reduction in greenness (deficiency) described earlier.

As discussed earlier, nitrogen has been linked to crop mark formation because of its close link with soil pH differences over ditches and other cut features, which affects microbial activity and therefore interrupts the nitrogen cycle (Figure 2.3 page 49). Despite its apparent importance, nitrogen concentrations could not be measured as part of the analytical work for this thesis due to financial constraints. The consensus on nitrogen's involvement in crop mark formation is that, as its effects are seen early on in the year when the soil is warming up and growing seasons are recommencing, it is unlikely to be associated with crop marks appearing in summer time, unless the effects of the earlier

responses continue to be visible throughout the growing season (D Moss pers comm). However, as nitrogen is the main factor in the amount of dry matter a plant produces and the greenness of that growth, it does have the most important visual effect on crops.

Soil structure has a direct effect on the rooting of plants. The deeper the roots of a plant can penetrate downwards the greater are the reserves of nutrients and water at its disposal. However, both nitrogen and organic matter content decrease with depth. If the soil is sandy, inorganic and mineralised, nitrogen may leach out of the reach of roots, especially if there is high rainfall (and also drainage), before the crop has developed a good root structure. This is most likely to happen in autumn and late spring when temperatures are such that mineralization of organic nitrogen occurs, then it rains and nitrogen is leached out of the profile as nitrate. It is less likely to happen in heavy clay soils as they tend to be cooler and more water retentive.

Wet autumns and springs tend to herald bad years for crop marks, which could be partly due to this lack of nitrogen in lighter soils. Conversely, heavier soils are less likely to allow loss of nitrogen by leaching, but because of a higher capacity to retain water these soils are generally less likely to produce crop marks despite the better retention of nitrogen. Hence it is difficult to say whether water or nitrogen availability, or a combination of both, prevents crop mark formation in these soils.

Nitrogen is known to have significant effects on the growth patterns of plants. LAI is strongly affected by application of nitrogen fertilisers, so intensive agricultural practices may negate climatic effects. As LAI is relevant to crop mark appearance, the role of nitrogen in the ability to detect buried remains aurally cannot be fully ruled out. Excess nitrogen in the soil causes lodging. The main reasons for enhanced nitrogen availability include the presence of more mineral nitrogen, more organic nitrogen, or it may be due to a difference in soil structure in areas of crop marks that affects rooting, and especially rooting depths. Differential lodging of the crop mark across a field has been noted, for example at Mollins Farm (Hanson and Maxwell 1984, and information from Prof Bill Hanson) where this was ascribed to the wind catching the tops of the relatively taller plants comprising the crop mark.

Extra mineral nitrogen is available to crops, as opposed to organic nitrogen which is not available to plants. Organic nitrogen may be mineralised into available nitrogen over a

scale of months or years. The rate of mineralization depends on soil conditions, with optimum conditions for bacteria associated with the conversion of organic nitrogen, being most active when the soil environment is warm and wet. Mineralization rates in dry soils are negligible. More organic nitrogen becomes available in the soil from anything that can yield manure. This could be the farmer spreading slurry or manure on the land, or other organic fertilisers. It can also be due to archaeological features and materials, such as midden deposits and enclosure fences and dwellings constructed from organic materials.

Nitrogen especially, and calcium, are indicated as being responsible for the formation of natural and archaeological crop marks.

Calcium

As Table 2.8 indicates, as a major constituent of the cell wall, calcium plays an important role in plant health and nutrition. It is also important for the maintenance of soil condition. It controls acidity and consequently the many chemical reactions taking place in the soil-plant system. It affects the microbial population responsible for many important processes such as nitrogen fixation and controls the activity of earthworms, which improve aeration and the structure of the root medium generally (Russel 1971, 442).

A deficiency of calcium can lead to other deficiencies appearing as chloroses in plant populations, that is a reduced greenness of foliage. For example, phosphorus becomes unavailable at low pH, with absorption by the plant optimised at a pH of around 6.5. More familiar to the gardener, and discussed briefly above, is lime- induced chlorosis, which refers to iron becoming unavailable to plants at higher pHs, which force the iron to become effectively 'locked up' in the soil due to a changed oxidation state produced by the alkaline conditions.

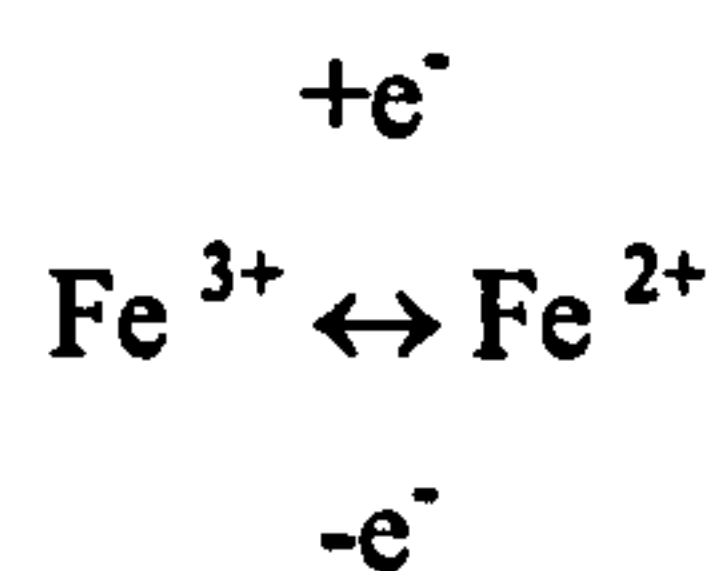
If a buried, mortared wall is present, the mortar can supply calcium and encourage differential growth above the wall. Theoretically this should lead to relatively enhanced growth up to a point where there becomes an excess of calcium, which would begin to impede iron uptake, producing the more traditional negative growth expected above a wall. However, this suggests that a more thorough investigation into a crop mark is

required to ensure that positive growth appearing above a wall due to locally more favourable pHs in soils inclined to acidity are not misinterpreted as cut features. This also has implications for magnetic survey as it affects iron chemistry and could similarly be used to add depth to the interpretation of anomalous areas.

Iron

Although dealt with in greater detail in Section 2.11, where its important role in soil magnetism is discussed, iron is briefly considered separately here for two reasons. First it is a very important soil element as far as magnetic survey is concerned, and second it has been suggested as the cause of the appearance of crop marks in Case Study 1, based on an examination of aerial photographs of the crop mark (W Fricke pers comm).

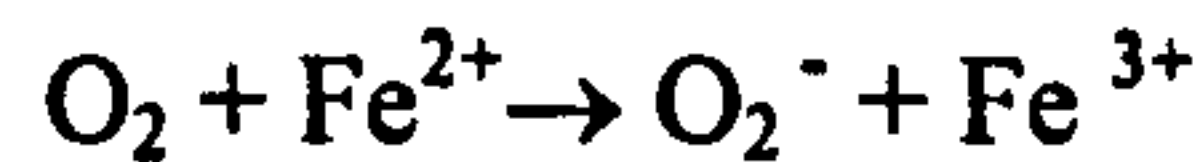
Iron is a transition element, and one characteristic of these elements is the relative ease by which they can change their oxidation state (Ebbing 1987, 866, 874-5).



Iron exists in various forms in the soil. In aerated soil systems maintained in the physiological pH range (around pH 6.5) as would be expected in cultivated soils, concentrations of ionic Fe (III) and Fe (II) are usually less than 10^{-15} mol. Therefore, chelates (chemical compounds that combine with free metal ions, abundant in organic matter) of Fe (III) and occasionally Fe (II) are the dominant forms of soluble iron in soil and nutrient solutions (Marschner 1995, 313). In aerobic systems many low molecular-weight chelates, and free iron in particular (Fe (III) or Fe (II)), are very effective at producing oxygen and hydroxyl radicals and related compounds, as for example in the Fenton Reaction:



Or other reactions such as:



(Marschner 1995, 313)

Iron also has the ability to form octahedral complexes with various ligands. In a ligand, which is a complex ion, the central or nuclear ion, which in this case would be iron, is surrounded by a series of ions, atoms or molecules, for example $(\text{CN})^-$ in the ligand $\text{Fe}(\text{CN})_6^{4-}$. Examples of ligands important to soils include organic acids and inorganic phosphate (H_2PO_4^- where the O of the anion displaces an OH or OH_2^+ group from the iron cation, a process known as ligand exchange (White 1987, 116). The redox potential of Fe (II/III) varies widely depending on the ligand (Marschner 1995, 313).

As a rule Fe (II) is taken up preferentially by plants, rather than Fe (III). This is dependent upon the plant species, and in the case for barley it has a mechanism for Fe (III) uptake, (Marschner 1995, 313). Most of the iron in plants is in the ferric (Fe (III)) form (Marschner 1995, 321). Iron is required for protein synthesis, and the critical deficiency content of iron in leaves is in the range of 50-150 mg Fe kg^{-1} dry weight. Iron supply is considered to be suboptimal when concentrations of Iron III chelates are low or sparingly soluble inorganic Iron III compounds are supplied (Marschner 1995, 323). Iron deficiency affects the size of chloroplasts and their protein content, and impairs photosynthetic electron transport. Only where there is severe deficiency does cell division become affected which causes a reduction in leaf growth, but anything affecting chloroplasts and photosynthesis will cause an appreciable colour change in the leaves (Marschner 1995, 319-20). Iron deficiency affects root development too, except in graminaceous species (the grass families), which is very pertinent when considering the general lack of negative crop marks (as opposed to parch marks) in grasses. These species release substances called phytosiderophores which act as chelating agents for Iron III compounds, making them available for uptake (Marschner 1995, 322-3). Perhaps this is one of the reasons why crop marks are slow to appear in grasses, and maybe also why geophysical responses in the permanent pasture in Case Study 3 were so poor compared to the other sites.

Conversely, iron toxicity ('bronzing'), brought about by excess uptake, is a serious problem on waterlogged soils. It may also have an effect under dry conditions, and is

thought to play an early role in drought-induced damage in photosynthetic tissue. This is due to its role as a catalyst in reactions that form oxygen free radicals in the chloroplasts, which have a very damaging effect in biological systems (Marschner 1995, 324).

So, to be available to plants iron must be in the Fe (III) state, and if it is not it must first be oxidised prior to uptake. Plants have a number of mechanisms by which they can effect this oxidation, which include the secretion of organic acids to lower pH locally in the rooting zone, or in the case of grasses by exuding chelating agents (Fricke, pers comm; Marschner 1995, 322-4, 653-4). Based upon this information, it seems highly probable that iron in detectable archaeological features exists in a different form to that in the rest of the field. This is especially likely where the crop marks and geophysical anomalies correlate, as in case studies 1 and 2. Changes in iron chemistry will almost certainly affect the magnetic susceptibility and the altered state of the iron, it is assumed, will also affect the potential current paths and therefore electrical resistance, across buried remains. This is discussed in more detail in Section 2.11 below.

2.5 Plant Responses to Soil Conditions

“Since plants are able to absorb certain elements preferentially, but cannot prevent the uptake of any one of them, the composition of their ash reflects the geochemical nature of the soil on which they grow.”

Larcher 1995, 177

The first organs to be affected by moisture stress in barley and wheat are the leaves (Orchard 1961), followed by the stem and finally the roots (Jones and Evans 1975). Moisture stress in cereals is most serious in the period before ear emergence (*c* early to mid July in Scotland, depending on the sowing date). The most obvious effects of what is assumed to be moisture stress that are recognised in cereals growing above buried archaeological sites occur above buried walls, foundations and other similar features that effectively reduce the depth of soil that crop plants are growing in, producing negative crop marks. However, as has been indicated, positive marks are much more common in Britain, although in other countries this may not be the case, for example Romania (Hanson and Oltean 2003). In this case, applying the soil science approach discussed earlier, the crop mark plants are growing optimally (as opposed to enhanced growth)

relative to the stressed plants in the rest of the field. The growth effects visible in either type of crop mark relative to the plants comprising the bulk of the crop include variations in height, colour and number of tillers (Figure 2.4). Jones and Evans (1975) suggest that crop mark visibility is associated with leaf area index (LAI) variations within the crop, as discussed earlier, as well as differences in plant colour and stem height, and this is examined in Chapter 5. Because barley has a larger LAI than other cereals, the contrast in leaf density between barley plants under water stress on shallow soils, and plants adequately supplied with water on deeper soils is greater (Jones and Evans 1975).

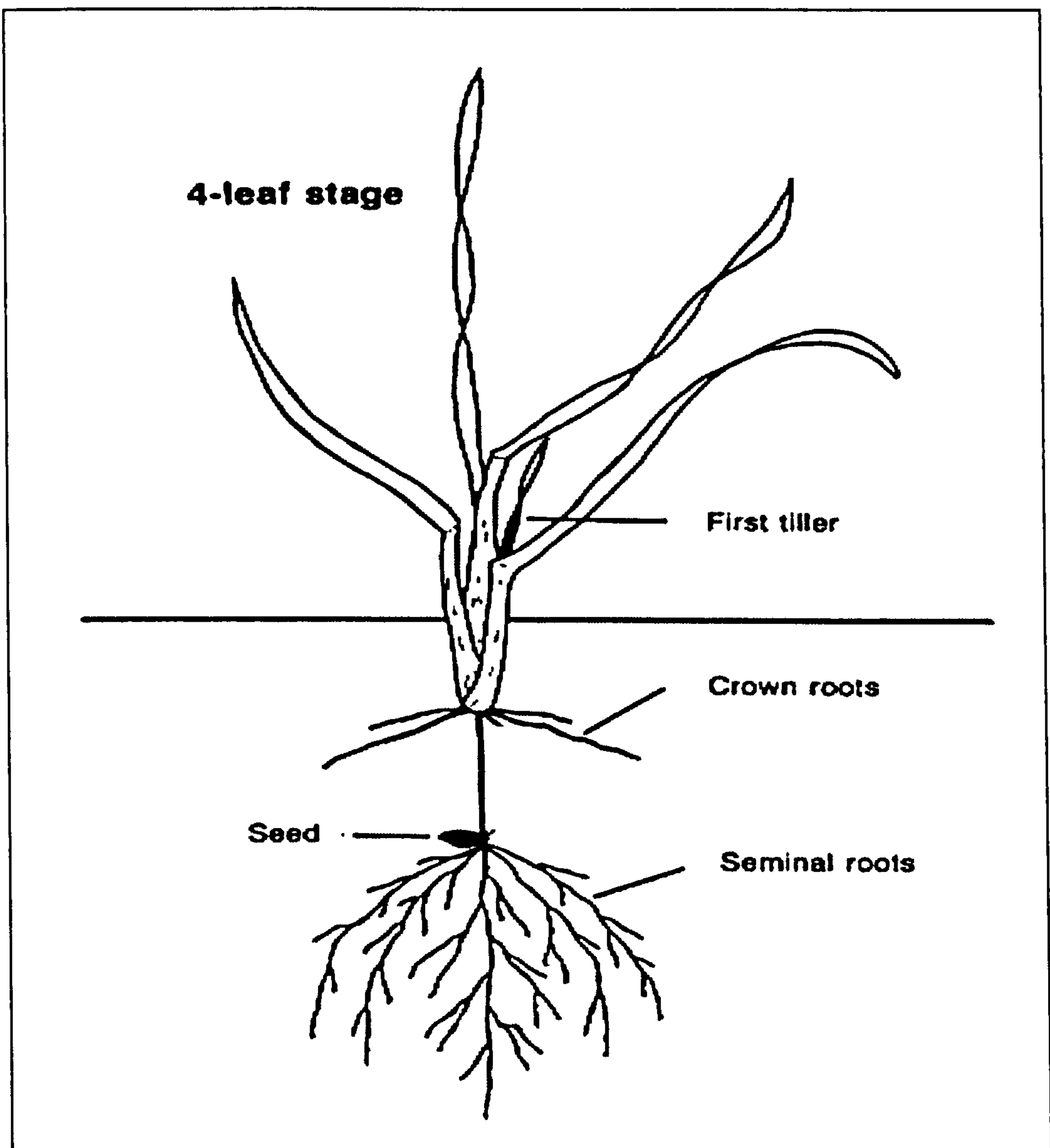


Figure 2.4:
Botanical diagram of a barley plant.

Plant responses to summer SMDs are influenced by the sowing date for the crop. This is rarely referred to in studies that reveal differential appearance of marks in adjacent fields. Riley comments "The most obvious differences are those due to winter or spring sowing, which considerably affect the state of growth of cereal crops in early summer." (Riley 1979, 30). He goes on to comment that:

"After a wet spring followed by a July drought,...the spring-sown crop may show distinct marks in the period of drought, while the autumn-sown may not, having passed through the critical stages while the ground was wet. There are many complications of this kind, but it is normal for marks to appear in both autumn- sown and spring-sown cereals, provided that they develop at all."

(Riley 1979, 35)

The initial cause of a crop mark can be differential germination, and these germination marks can sometimes be seen as early in the year as December (Riley 1979, 30). The marks are associated with the soil temperature differences discussed above, which results in differential crop densities across the field associated with germination success. Other later density differences are thought to be due to the number of tillers each plant produces. Tillering frequency is affected by environmental stresses. Jones and Evans attribute the lower visibility of crop marks following heavy rain as being due to a stimulation of tillering in the individual plants once the SMD is reduced and that particular stress is removed. St Joseph also noted this in 1965. He photographed distinct crop marks on a gravel terrace at Great Shelford near Cambridge on 17.6.60. Three days later, after 7 mm of rain on 19.6.60, the tonal contrasts were less marked, the growth restriction having been removed and tillering stimulated (1965, 60-1; 143-5).

An examination of this response, together with differences in root growth between crop plants growing above archaeological remains and the rest of the field, is a critical factor that requires to be investigated. However this, and particularly the latter, is seen as "entirely the study of the agricultural botanist" (1965). These factors are addressed in part in the pot-based experiments discussed in Chapter 5.

Traditionally, as discussed earlier, there are two kinds of crop mark, positive and negative, which are described as enhanced, darker growth in the case of the former and

stunted, lighter green growth in the case of the latter type. So here we consider what causes barley plants to appear as darker green, and what causes them to appear as lighter green areas on aerial photographs. What must also be considered is that these marks appear *relative* to the plants growing in the rest of the field, beyond the influence of the underlying archaeology. In effect, we are examining the factors that cause these three types of growth: normal, enhanced and impoverished.

A healthy barley plant will be a rich green colour, with dense growth; the result of the production of a good number of tillers, and it will have a reasonably compact growth habit (the characteristic growth pattern associated with individual plant species, including height, spread, shape and form of growth). Anything other than this indicates that one or more cultural factors are not as they should be.

Returning to the plants comprising crop marks, it is easy to see the positive marks in terms of nutrient excesses and the negative marks as nutrient deficient plants. In this case an excess may not indicate an excessive amount of certain elements taken up by the plant, but rather an excess available relative to the rest of the crop plants in which the particular nutrient has become limiting. This does not mean that a farmer whose field contains an archaeological crop mark has not provided enough nutrients to the whole of the field. As stated earlier it suggests that parts of the crop associated with the archaeological site have access to an additional supply that in the rest of the field is limited due to plant uptake as the growing season progresses.

This leads us to the next question. Is the positive response due to an actual enrichment of the limiting nutrient because of some anthropogenic activity or pedological process, or is the limiting nutrient simply more easily available in the area of the archaeological remains because they are affecting one of the other growth factors, such as soil texture or moisture holding capacity?

The latter is the easier to address. There are two reasons why archaeological remains could cause enhanced growth. Assuming, as is the accepted explanation, that the remains associated with the positive growth are a cut feature the enhanced growth could simply be a response to a larger volume of topsoil filling that feature, which by its nature would contain a larger volume of nutrient elements than an area of undisturbed ground with a shallower depth of topsoil. An analogy would be to grow a given number of barley plants

in a small plant pot, and the same number of plants in a pot twice as big for the same length of time. Without the addition of fertiliser, the plants growing in the smaller pot would run out of nutrients in a shorter time than those in the larger pot because the smaller volume of soil would hold a smaller amount of nutrients. As will be seen in Chapter 3, this assumption is tested in my experimental work by examining both archaeological soils and plants grown in them for elemental concentrations. If there are differences between the elemental compositions in the plants grown in different archaeological soils, it rules out the 'bigger reserves' hypothesis, as soil volume is a variable that is effectively removed from the equation in the glasshouse experiments. In other words, if there are differences between plants grown in different archaeological contexts, but in the same size of pot, these must be due to enhancements or depletions in the archaeological soils rather than there just being more of a particular element available because, for example, there is a larger volume of the fill, as would be the situation in a deeply cut archaeological feature (see Chapter 3).

Alternatively, the cut feature and the surrounding soil may hold approximately the same amount of nutrients, but the underlying features could change other growth factors. This applies especially to the drainage of the soil profile and so the amount of water that the soil filling the feature can hold. This is discussed in more detail below, but briefly, any changes in the ability of the soil to drain or to hold on to pore waters can affect the oxidation state of the soil and the elements held within its pore spaces and solution.

This has two effects on the nutrient elements. First it can change the oxidation state of the elements themselves, and second it can change the soil's ability to hold onto them. For example, if a soil becomes waterlogged it cannot hold as much oxygen because this is displaced by the water, causing the soil environment to become reducing and more acidic. This will bring about a change in the oxidation state of the ions present in the soil. A relevant example here would be the change of Fe (III) ions to Fe (II) ions, which is also discussed above. Other ions that are capable of reaching toxic concentrations in an anaerobic soil environment include manganese (Mn^{2+}) and Hydrogen sulphide (H_2S) (Larcher 1995, 375). As will be seen, the oxidation state of the elements is important to their availability for uptake. In some cases, again iron is an example, plants are only able to use the elements in certain oxidation states, and in other cases the oxidation state affects the solubility of the ion, and again the uptake in solution (W Fricke pers comm).

Certain elements are more mobile in soils than others, for example nitrogen and calcium. If the soil has a high throughput of water these less-stable elements can be leached out of the soil to be held at depths which make them unavailable to plant roots, for example iron and manganese pans.

Returning to the first question arising when considering positive crop marks, the possibility exists that the human occupation of the buried site resulted in certain elements being concentrated in the remains left after the site was abandoned, or that certain activities caused the enrichment. An analogy is that just as the waste of human and animal habitation was gathered in middens and then spread onto the fields as fertilisers before the advent of modern chemical soil conditioners, so an occupation site, as the generator for this waste, may become visible aerially and geophysically as a result of being the automatically enhanced core for fertiliser production.

A more traditional example, taking the site of a settlement's midden, is that the deposits containing the remains of animal carcasses, dung and human excrement and food waste could cause an enrichment locally of calcium or phosphorus because of the presence of bone and organic materials. Alternatively, fermentation reactions occurring within the midden as the organic material decomposed could raise temperatures high enough to cause the oxidation of iron minerals naturally present in the soil, a pedological rather than directly anthropogenic effect.

As mentioned, the roots of cereal plants tend to occupy the top 30 cm of soil in a field. Russel (1973) has demonstrated that 90% of barley roots lie within this depth. Further work has demonstrated that the distribution of roots down a soil profile strongly correlates with the uptake of calcium and phosphate by the crop. This may provide a link between phosphate sampling, which has proved its worth in archaeological settings, and crop mark formation, with positive growth being linked to a well-developed root system. This will be discussed further in Chapter 6. Table 2.8 summarises the main effects of the elements known to affect plant growth. In grasses, certain elements are incorporated preferentially into the foliage, including nitrogen, phosphorus, calcium, magnesium, sulphur and silicon. In contrast flowers and fruits tend to store mainly potassium, phosphorus and sulphur (Larcher 1995, 176).

Table 2.8: Effects of Nutrient Elements on Plant Growth

Element	Role in Soil-plant System	Deficiency	Excess
Nitrogen	Governs dry matter production and greenness	Reduced greenness; Inhibition of tillering	Lodging
Phosphorus	Essential for many metabolic processes	Causes purpling of stems and leaves in barley and wheat, and thin growth	
Potassium	Seed and fruit production	Stunted, brittle growth	
Sulphur	Protein component		
Calcium	Important for cell structure; controls acidity and therefore many soil-plant chemical reactions, including microbial and earthworm activity, thus affecting eg N uptake and soil aeration	Chlorosis due to impeded uptake of eg P at low pH (ie relatively less Ca)	In grass encourages growth of clover (trifolium sp.) and thus may produce vegetation marks. 'Lime-induced Chlorosis', caused by impeded uptake of Fe (ie relatively higher Ca levels)
Magnesium	Essential constituent of chlorophyll; carrier element for Phosphorus	Can cause colour variations in cereals	
Iron	Chlorophyll component		
Manganese	Essential role in photosynthesis	Chlorosis, suppression of tillering, reduced stem growth induced at greater than pH 6.5, wetness is a contributory factor during early growth	'Bronzing'
Copper		Dark patches in cereals, visible from a distance, linked with high soil pH	

2.6 The Move Towards Linking Crop Marks to Geophysics

As will be seen in Chapter 4, the underlying geology can affect crop growth when there are local small-scale changes. An example is a type of limestone, known as Cornstone, so-called because it is known to produce enhanced growth in overlying cereals ('corn') where it outcrops (British Geological Survey help desk pers comm). Coming as no surprise given the preceding section, this shows that even geological crop marks occur in response to chemical differences in soil associated with the underlying geology. In this case there is more lime in the overlying soil and therefore the pH is altered, causing changes in crop growth. So why should archaeological crop marks be described purely in terms of differences in water holding capacity? Clearly pH does have an effect on crop mark appearance. The most obvious explanation for this, as the section on calcium and Table 2.8 indicate, is that pH affects the mobility of nutrient ions, and is implicated in the maintenance of soil condition. This affects the proportion of pore spaces in a given volume of soil and consequently in the availability of pore waters. The amount and concentration of the soil solution affects the ability of the nutrients present to reach plant root hairs, and be used by the plant for metabolism.

Water is essential for plant growth. It is involved in almost all major metabolic processes and also plays an important role in the rigidity of the plant structure. As the growth experiments detailed in Chapters 3 and 6 will show, water has a big influence on the appearance of the plant, not least due to the loss of cell turgidity when water availability is limited. The results of the growth experiments together with the literature help to illustrate the importance of the role of water in crop mark formation. The soil solution, as opposed to water *per se*, provides a very important link between the results of aerial reconnaissance and geophysical survey, which is fundamental to this thesis. Before this link can be fully explored, however, we must examine the way in which electricity and magnetism are associated with the soil, and so must look at electromagnetic theory. Magnetism and electricity, as will be seen, are intimately linked. By examining these properties at an atomic level, it becomes clear that the ionic properties of the elements present in the soil solution link the altered growth of crop marks with anomalous responses recorded geophysically. Effectively, by applying this theory the archaeological site is reduced to a series of changes in the concentrations of ions and electrons held within the soil.

2.7 Electromagnetic Theory

Electromagnetic theory describes how electrical charge occurs at an atomic level and how that generates an associated magnetic field. There are many books available that explain electromagnetism in depth (eg Ryan 1986; Grant and Phillips 1988), so only an outline of the theory as it is seen to be relevant to this thesis follows.

Many substances associated with soil and plant chemistry are ionic, gaining or losing electrons from their atomic structure easily, and this is the basis of ionic bonding in chemistry (Ebbing 1987, 247-51). Those electrons that are removed from orbit around ionic substances are known as free electrons (Ryan 1986, 4). A substance that allows the movement of a large number of free electrons within it is known as a conductor, a classic example being copper. Electrical current, such as that carried along a copper wire is the movement of electrical energy by the free electrons from each copper atom, which are forced out of their orbits and moved along the wire in the presence of an applied electrical force. If there are no free electrons in a substance, there can be no electrical current within it and such substances are known as insulators. Examples of insulators, where all the electrons are tightly bound to the nucleus leaving very few free electrons, include glass, rubber and dry wood (Ryan 1986, 5-6). An electrical field is defined as the space between and around charged bodies in which their influence is felt (Ryan 1986, 12).

When an atom loses electrons it becomes positively charged. A negatively charged atom contains too many electrons, and in both cases the orbiting electrons do not balance the charges on the nuclei. This situation is common in ionic substances present in soil water. If a positively and negatively charged ion come into contact an electrical current will flow between them. This occurs as electrons transfer between the two ions in an attempt to reach an equilibrium, the natural, lowest energy state that chemical systems seek to attain. In this case, the electrons leave the negatively charged ion and enter the positively charged one until the electrical charges on each are equal (Ryan 1986, 12).

The force that causes free electrons to move as a current in a conductor is known as the electromotive force (emf). It is also known as the difference in (electrical) potential or the voltage (see Table 2.9). When there is a difference of potential between two charged bodies connected by a conductor, electrons will flow along it from the negatively charged body to the positively charged one. This flow represents the electric current, which can

either be a direct current (DC) or alternating current (AC). In the former, the current does not change the direction in which it flows, whilst in the latter there is a periodic reversal in flow direction. Current flow through an electrical circuit is directly proportional to the potential difference across the circuit, so if voltage increases or decreases, the current increases or decreases accordingly (Ryan 1986, 21-23). The amount of current that flows in a given circuit depends on not only the voltage, but also the resistance in the circuit. Resistance is defined as the ability of a material to impede the flow of electrons, and is obviously important to the discussion on geophysical survey at archaeological sites.

The principles of electricity and magnetism are interrelated. Like electricity and electric fields, magnets and magnetic fields follow the laws of attraction and repulsion. In the case of magnetism, the points of maximum attraction, the north and south poles, behave according to these laws, with opposite poles attracting and like poles repulsing. In a magnetic field associated with the simplest situation, a bar magnet, the lines of magnetic flux that comprise the field emanate from the north pole and return to it through the magnet, re-entering at the south pole. In a similar way, the current in an electrical circuit flows out from the negative terminal of a battery and returns to the positive (Ryan 1986, 21-2; 112-14). Emf can be produced in a conductor that is moved in a magnetic field (Ryan 1986, 28).

In 1819, the Danish physicist Hans Christian Oersted discovered the definite relationship between magnetism and electricity. He established that an electrical current is accompanied by certain magnetic effects that obey definite laws (Ryan 1986, 119). In the case of a current-carrying wire, the associated magnetic field exists at all points along its length, and the magnetic field comprises concentric circular lines of flux running perpendicular to the wire (Ryan 1986, 122). For all electrical fields, a magnetic field exists around it with a plane at right angles to the direction of the electrical field.

There are three types of magnet, only two of which are pertinent to this discussion. Permanent magnets are commercially produced ones that involve processes that magnetise steels and other alloys, and are not discussed here. Natural magnets, such as magnetite are very important to magnetic prospection, and are discussed further below. Finally electromagnets are those that comprise a coil surrounding an iron core. When an electric current is passed through the coil a magnetic field is produced for as long as the current flows. This is the principle upon which the fluxgate gradiometer works, the

magnetometer type used in the surveys at the Case Studies for this thesis. In this case the core is mu-metal, which is a very magnetically sensitive iron alloy core, and the instrument (Geoscan's FM36) contains two magnetometers (see Chapter 3), hence the name gradiometer as opposed to a single magnetometer. The FM36 allows the vertical gradient of the magnetic field to be sampled. During survey the magnetometers effectively work constantly as magnets, for when the current in the primary coils around each core is off, the cores become magnetised by the local geomagnetic field. This produces an emf in a secondary coil around the cores (Ryan 1986, 133), which is translated into a reading of vertical field strength at the measuring point.

Traditionally only certain types of material are thought of as being magnetic. These are metals, and specifically iron, nickel and cobalt. In metals the free electrons are known as Conduction Electrons, and contribute towards the material's magnetic properties (Grant and Phillips 1975, 170). The electrons can conduct electricity and therefore can develop a magnetic field perpendicular to the flow of current. The ions within the lattice structure of the metal may also contribute to the total magnetic properties. The arrangement of electrons and ions can cause a material to be either paramagnetic or diamagnetic (Grant and Phillips 1975, 170), and these terms are discussed briefly below. Non-metals are considered to be non-magnetic. However, we know that a current-carrying conductor is capable of producing a magnetic field around itself. Additionally, under certain conditions, such as when there is relative motion between the conductor and magnetic field, that magnetic field may also induce an emf in the conductor (Ryan 1986, 133-4). As a conductor moves in a magnetic field, it cuts the lines of magnetic force and when this happens current flows as long as there is a complete path for the current to flow in the conductor (Ryan 1986, 134). This is known as electromagnetic induction, and forms the basis of AC electrical current generation (Ryan 1986, 134-55). Because we are considering the common ground between the detection of sites aerially and geophysically, this concept is very important. We know that geophysical survey detects changes in the subsurface, and that the aerial identification of differential plant growth indicates that the changes responsible for both are primarily within the soil, extending to the subsoil, and possibly the drift geology. The analysis of the possible causes of differential growth in crop marks increasingly points towards a soil chemical explanation linked to the availability of soil moisture. Increasingly this explanation for detectable differences at archaeological sites is being directed towards the soil solution. Electromagnetic theory now requires us to look more closely at the behaviour of the ionic compounds in solution

in soil water, and ask could they be responsible for differential plant growth and also, as a result of electromagnetic induction, for magnetic and electrical anomalies?

Electrical conductivity (σ) is the mathematical inverse of resistivity. The electrical conductivity of a soil, defined by Ohm's Law, is the constant of proportionality between the current (I) and the emf (E):

$$I = \sigma E$$

(Scollar *et al* 1990, 19)

Electrical conductivity (or just conductivity) is the term used in preference to resistivity by most soil scientists and other life scientists to describe movement of electrical charge. Conduction in soil is electrolytic and based on the displacement of ions (or perhaps more accurately electrons removed from ions) in interstitial water. As such, soil conductivity is increased by the presence of dissolved salts and water (Scollar *et al* 1990, 19). If dissolved salts, the nutrient elements taken up by plants, carry charge and have the capacity to conduct it, they then also have the ability to produce magnetic fields. If this is the case, then all dissolved salts must theoretically contribute to the magnetic fields detected at archaeological sites, and not just those traditionally regarded as being magnetic, namely iron, cobalt and nickel. This interpretation assumes that movement of the ions within the soil water, and within the earth's magnetic field creates an emf within the soil solution, and hence, according to EM theory, an associated magnetic field. However, there are some drawbacks to this suggestion, not least the problems of how the electrical currents are produced within the soil, unless by an emf as described. There are DC earth currents present in the ground which could provide the electrical force needed to drive the currents (D Sanderson pers comm), and this is witnessed by the fact that the RM15 used during survey has a filter built into the instrument to prevent interference from these currents. However, there is a natural source of current production within the soil, and this is based upon the principle of electrokinetics. Clay minerals present in the soil have surfaces that possess a net negative charge, and this results in electrostatic phenomena (Nielsen 1972, p39), and is naturally more pronounced in clay soils. Cations are held in the vicinity of these surfaces mainly by the electrostatic forces present, and the energy of these electrostatic bonds is of the same order of magnitude as the thermal energy associated with the soils. Because of this, the adsorbed cations often gather enough translation energy from other molecules to become temporarily dissociated from

the charged surfaces into a 'diffuse layer' (Nielsen 1972, 39). The ionic distribution within the soil is, according to Gouy Theory, the result of two forces. These are the electrostatic forces that cause the cations to move towards the negatively charged surfaces, and a thermal motion which causes them to diffuse away from the region of highest concentration near the charged clay surfaces (Nielsen 1972, 40). The result is an unequal distribution of cations and anions due to the charged clay surfaces. So, as water moves in the soil some of the ions are swept along with the water which causes a charge to build up across the length of the flow, which tends to retard the flow, and is known as the streaming potential (Nielsen 1972, 47). If an electrical potential is applied across the flow system the ions will be pulled towards one end, carrying water with them.

In a soil-water system temperature and osmotic gradients exist which can induce water flow. One such osmotic gradient is that produced by nutrient uptake at plant roots. Other osmotic gradients exist where salts are unequally distributed within a soil-water system, such as is proposed here. Water will then flow from points of low to higher concentrations, and in the process some of the salts involved will diffuse towards the points of lower concentration and some will be carried along in the water. The moving water can carry heat or dissolved salts in it, which will alter the driving gradients (Nielsen 1972, 50). At the time of writing (1972) this theoretical description of such simultaneous flows had not been fully developed. However, a later publication (Richter 1987, 113) describes electrical currents produced in the soil environment by cations and anions flowing in the solute which generate electrokinetic and osmotic phenomena in the ionic soil solutions (solute flow), as well as volume flow of the soil water itself. This produces a current potential (voltage) due to a volume flow within a salt concentration, and supports the hypothesis that magnetic anomalies present at sites are not just a consequence of there being magnetic compounds present, but also depend upon salt concentrations within the soil. The important point to note, apart from the obvious one that all soil systems are very complicated and many are still not fully described, is that these gradients provide the mechanism for water flow and electrokinetic behaviour provides a source for the generation of currents within the soil-water system that EM theory predicts will have associated magnetic fields induced. The electrical resistivity of a soil depends on its composition and texture as well as water content and soluble salt concentration. The important point to note here is that experimentally measured resistances for moist porous blocks depends primarily on the permeating fluid rather than the solid matrix through which it flows, and therefore resistance depends on the

electrolytic solutes present in the fluid as well as the volume content of the fluid, and this statement applies equally to soils (Ashman and Puri 2002, 60). This allows a fuller than normal consideration of the production of resistivity and magnetic anomalies that can be linked together with the development of crop marks.

If this is the case, then altered levels of ions in certain areas of crop mark sites, namely where there are positive or negative crop marks recorded, should coincide with similarly enhanced or subdued responses to magnetic and electrical survey. As will be seen in Chapter 5, we know this to be true for many sites, and specifically at two of the three Case Studies presented. To move this hypothesis from the realms of theory into certainty, we must determine whether there are altered elemental levels at the sites of differential crop growth. If these elemental differences can be identified, and this is covered in Chapter 6, it then remains to determine which elements are present in concentrations significantly different to cause differential plant growth, resistivity anomalies and, probably most significantly, magnetic anomalies. Specifically, rather than the standard interpretations for geophysical anomalies at sites, which tend to be fairly 'black box' (ie electrical charge is introduced, attenuated and measured), or 'large-scale' (ie magnetic anomalies = presence or absence of iron) in nature, it may be possible to determine whether the responses are explainable at this atomic level. However, this thesis can only take the investigation so far, and must be considered a starting point for further investigation. For example, it is beyond its scope to attempt to determine empirically whether the sum of the magnetic fields produced due to the flow of current in the soil solution is responsible for the magnetic anomalies. It should be possible to determine to what extent the three remote sensing techniques are effectively measuring the concentrations of dissolved ions in the soil solution in a qualitative manner, but again not within this work. It will, however, be possible to say which elements are contributing most significantly to the overall effects that are a starting point for any further work, which is a logical hypothesis following on from the consideration of electromagnetic theory outlined here. This will all be assessed critically in Chapter 7 in the light of the experimental work introduced in the following chapters.

2.8 Geophysics

“Of course there are occasions where a geophysical survey produces such a complete plan that valid archaeological interpretation is possible without excavation, but such occasions are rare.....”

Aitken 1974, 187-8.

Introduction

The theory behind both of the survey techniques considered here, electrical resistivity and magnetometry, is well documented, as is the historical development of survey, and it is not intended to discuss this in depth. The abundant literature on the subject, which includes instrument design and use can be found in many texts (eg Aitken 1974; Clark 1990; Scollar *et al* 1990; Keary and Brooks 1991; Gaffney and Gater 2003; Geoscan Research Ltd manuals). A brief outline of the techniques as they are seen to be relevant to the work undertaken in this thesis is presented, although the electromagnetic theory discussed covers particularly the ideas upon which resistivity survey are based.

Prospection Methods

According to the traditional approach, magnetic survey for archaeology depends on local enhancement of already present iron minerals within soils, subsoils and often bedrock by the actions of humans. These actions may be either direct, such as lighting fires in hearths or kilns, or indirect, for example due to disturbance of soil profiles and upcasting of bedrock in cut features. Different responses are recorded over different types of enhancement. For example, an *in-situ* area of burning, which has not been disturbed since the event, will produce a characteristic dipolar response on a magnetic plot, representing a strong perturbation in the otherwise constant field measurement of an undisturbed Earth. Topsoil is usually more magnetically susceptible than subsoil, and generally, unless there are very iron-rich lithologies underlying the drift and soil profile, the magnetic susceptibility decreases with increasing depth below ground. Hence, while excavated features silted or backfilled with topsoil tend to give positive magnetic signals; less magnetic materials intruding into topsoil, for example magnetically quiet masonry, give negative signals (Clark 1990, 66). This means that any disturbance of the natural soil profile will cause lateral changes in magnetic susceptibility of the layers involved, and these changes are recorded during an area magnetic survey, and also are reflected in

overlying crop plants. Effectively, magnetic survey is thought to respond to subsurface areas that contain iron minerals and oxides that exist in states dissimilar to those contained in the surrounding undisturbed areas. The formation of coherent patterns and the intensity of the response from these areas in conjunction with the experience of the interpreter are all factors that assist in the interpretation of anomalous areas as of anthropogenic or natural origin.

Resistivity survey involves the measurement of the way in which an electrical current passed into the ground is attenuated as it travels through the subsurface layers. It is based upon the principle that if a medium easily conducts electricity, the resistivity will be low, and if it does not, the resistivity will be high. This allows variations in readings to be recorded which, as with magnetic data, can be output as an area plot which indicates the positions of low and high resistance corresponding to changes in the subsurface conditions within the survey area. Resistivity survey exploits Ohm's Law, which states that the intensity of the current (in amperes) in any electrical circuit is equal to the difference in potential (in volts) across the circuit, divided by the resistance (in ohms) of the circuit. Mathematically this is expressed as $I=E/R$. This means that if either resistance increases or voltage decreases, then current decreases. In the instrument used during the surveys undertaken for this thesis (Geoscan's RM15) current is kept constant throughout the survey which allows resistance to vary depending on the conductivity of the materials through which the current is directed (Clark 1990, 33). In this case, using ohms law, $R=E/I$, or resistance = the voltage divided by the current

Soil Magnetism and Magnetic Susceptibility

Le Borgne (1955; 1960) began the study of soil magnetic properties in the 1950's, with others following over the next decade or so (eg Cook and Carts 1962). Le Borgne recognised two mechanisms for the enhancement of magnetic susceptibility in soils and in archaeological features. These are heating due to burning or fermentation (Scollar *et al* 1990, 397; Aitken 1974, 221), and enhancement by bacterial action (Scollar *et al* 1990, 397). Enhancement was assumed to be due to the conversion of weakly magnetic haematite to maghaemite, which has a magnetic susceptibility around two orders of magnitude greater than haematite, via magnetite (Aitken 1974, 221). Later laboratory measurements of the processes confirmed Le Borgne's findings by establishing that the heating of any soil under reducing conditions (eg in the presence of organic matter)

increases the magnetic susceptibility by producing magnetite. This is then oxidised to maghaemite in subsequent aerobic conditions (Tite and Mullins 1970b; Mullins 1974; Tite and Linington 1975; Graham and Scollar 1976).

Although probably first noted by Tucker (1952), Le Borgne was the first person systematically to study the anomalously high magnetic susceptibilities recorded in various topsoils, and to offer an explanation for the phenomenon. This work established the fact that magnetic susceptibility generally decreases with depth, with the highest values found in the A-horizon of soils and the lowest in the underlying parent materials. Susceptibility has been shown to decrease by up to two orders of magnitude over the first metre depth of soil (Aitken 1974, 221).

A material that has magnetic susceptibility is only magnetic in the presence of an external magnetic field (Clark 1990, 65), although because the geomagnetic field is always present induced magnetisation in a material is very unlikely to disappear. To a magnetometer there is no practical difference between the measurement of permanent and induced magnetisation. Therefore, variations in magnetic susceptibility between archaeological fills, topsoils, subsoils and geological materials make detection of archaeological features possible.

Magnetic susceptibility in soils is essentially a measure of their iron oxide content and an indication of the oxidation state, and hence magnetisability, of the iron compounds. If there has been no disturbance due to past human activity in an area, the histograms of soil susceptibility produced by intensive sampling over large areas tend to be unimodal. The histograms become multimodal as sampling is conducted over long occupied archaeological sites (Scollar *et al* 1990, 402-3). The enhancement measured in anthropogenically altered soils depends on the concentration of organic matter and iron in the soils and the extent and duration of the exposure of the soil to burning (Aitken 1974, 190).

The weights of magnetic iron oxides in soils range between 0.5 – 5% (Graham and Scollar 1976). Magnetic particles have been found to be distributed uniformly throughout the soil matrix, which is itself normally diamagnetic (see below) due to the presence of particles including quartz, feldspars, calcium carbonate, and other non-magnetic minerals. Increasing the concentration of magnetic iron oxides decreases the distance within the

soil matrix between adjacent magnetic particles. Because the fields between the dipoles created by these magnetic grains decreases as the cube of the distance between them, the degree of interaction of the dipoles depends on iron oxide concentration within the soil. When close together, single domain grains behave like multiple domain grains, so that at high iron concentrations magnetic viscosity effects (hysteresis caused by molecular friction, defined as the time lag between the intensity of magnetisation and the magnetising force producing it, with shorter lags measured for more easily magnetised materials) are suppressed (Scollar *et al* 1990, 395-6; Ryan 1986, 127). Conversely, the greater the dilution of the grains as the iron oxide content decreases, the greater becomes the magnetic viscosity of the soil. Effectively this demonstrates why measurable magnetic susceptibility is lower in soils with lower iron concentrations. Le Borgne, however, has demonstrated that for field strengths of relevance to archaeological prospection, magnetic viscosity is almost independent of field strength (Le Borgne 1960)

In the 1980's much interest was aroused in the potential of magnetic susceptibility measurements to identify palaeosols in long Quaternary stratigraphies. This led to a large number of publications concerning the authigenic and diagenetic processes that may explain the susceptibility enhancement. At this time, biogenic magnetite (Fassbinder *et al* 1990) and greigite were found in archaeological sediments, suggesting that several processes may be in competition in the magnetic changes produced in soil. Several authors have attempted to explain magnetic signals from archaeological prospection by separating the anthropogenic and 'natural' signals (see Clark 1990, 103). The ability to detect archaeological features is thought to depend strongly on the susceptibility of the upper soil layers, and their ferrimagnetic mineral content, irrespective of their origin (Scollar *et al* 1990, 161)

Iron Minerals and Geological Changes

The strength of the Earth's magnetic field and the electrical resistivity measured at any given point varies slightly depending on the underlying geology at each measurement point. If a rock unit has a large proportion of magnetic minerals in it, a higher reading than the average will be recorded. Rock units devoid of magnetic minerals will give a relatively lower reading. Magnetic minerals are those that contain iron in a magnetic form, including haematite, magnetite and maghaemite as discussed earlier. Haematite is a common iron oxide, but does not contribute to magnetic fields because it is

antiferromagnetic (Keary and Brookes 1991, 148). Conversely, the presence of magnetite is responsible for the large magnetic effect of basic igneous rocks and is important to magnetic survey (Keary and Brookes 1991, 151-2). Non-magnetic iron minerals include the hydrated iron oxide, limonite. So, geologically significant readings would be seen at an interface between basalt, an igneous rock rich in ferromagnesian minerals, and limestone, often comprising pure calcium carbonate. Resistivity is also likely to change at this point due to the much more permeable nature of limestones compared to the hard crystalline structure of basalt, which tends to be impermeable to water. In this case resistance would also decrease as measurement proceeded onto the limestone, especially if the limestone were water-saturated. These differences in readings are the basis on which underlying geological trends are recorded and identified.

Although most rock-forming minerals are non-magnetic and do not have high magnetic susceptibility, certain rock types contain enough magnetic minerals to produce significant anomalies. Examples of these include the iron-titanium-oxygen group, which forms a solid solution series of magnetic minerals, and the iron-sulphur group, which includes pyrrhotite (Keary and Brookes 1991, 148-151). Sedimentary rocks can effectively be considered to be non-magnetic unless they contain magnetite within the heavy mineral fraction of the sediments (Keary and Brookes 1991, 152).

Traditionally it is thought that the main source of magnetism in a soil is its iron content (Scollar *et al* 1990, 386). The content depends on the parent materials from which the soils are formed, and this varies according to the lithological properties as described above. However, as discussed earlier and following on from the discussion on electromagnetism, it is possible that the electrical properties of the soil are in part also responsible for the magnetic properties.

As suggested, at an atomic scale, all substances are magnetic due to the rotational properties of the electrons in the outer shell comprising the material's atoms (Scollar *et al* 1990, 378-9; Clark 1990, 64; Keary and Brookes 1991, 150; Grant and Phillips 1988, 170; Ryan 1986, 126). Moving from individual atoms to substances, their magnetic behaviour depends on the arrangement of ions within their crystal lattice, which determines the way the magnetic fields of individual electrons react with each other and whether individual fields reinforce or oppose each other (Clark 1990, 64). The arrangement of electrons about the ions determines the magnetic properties of the

material that they comprise. The result is that a material can be described as ferromagnetic, diamagnetic, paramagnetic or ferrimagnetic (Table 2.9).

When a diamagnetic material is placed into a magnetic field, all of the atoms and molecules within it acquire magnetism due to induced dipole moments. These induced magnetic dipole moments are weak and are in a direction opposite to the applied field. This is known as Lenz's Law and is associated with the orbital rotation of the electrons about the nuclei of the particles comprising the material (Scollar *et al* 1990, 380). This means that diamagnetic materials placed in a non-uniform field experience a force in the direction of decreasing field strength. On an atomic scale, the atoms or molecules are said to be magnetised. Averaged over a volume of material the individual magnetisations of each particle, which slowly changes with position in the magnetic field, gives the magnetisation of the medium. This is defined as the magnetic moment per unit volume and is expressed in Amperes per metre (Am^{-1}) (Grant and Phillips 1988, 134). The magnetic susceptibility measured under these circumstances is of the order of -10^{-5} . In the presence of more highly magnetic materials, such as ferromagnetic substances, the stronger positive susceptibilities of these materials will mask this weak diamagnetic component of the magnetisation (Scollar *et al* 1990, 380).

In areas that have been intensely settled by humans it is impossible to separate the effects of significant concentrations of naturally occurring paramagnetic minerals from the magnetic effect of ferrimagnetic minerals, such as maghaemite, which has been demonstrated to be the only significant oxide producing this ferrimagnetic input (Longworth and Tite 1977). In the same study, despite it being the most common magnetic oxide of iron, magnetite was shown to be an insignificant component of agricultural soils outside of volcanic areas. However, even if present in very small quantities, it has a significant effect on soil magnetic properties. Although the presence of magnetite in archaeological soils has not yet been demonstrated, it is important because of its relationship to the remaining two archaeologically significant iron oxides, maghaemite and haematite (Keary and Brookes 1991, 151; Scollar *et al* 1990, 388). In a magnetite crystal, certain sites are occupied by ions of iron, some of which are in the Fe(II) state and an equal number exist as Fe (III) ions. Of the Fe (III) ions, there are equal numbers of magnetic moments in opposite directions and so these moments cancel each other. This leaves the magnetic moments of the Fe (II) ions, which are not coupled and so impart a net magnetic moment or a permanent magnetisation to the crystal (as opposed to

it having magnetic susceptibility), which is equal to the sum of the individual net magnetic moments present within the crystal structure (Scollar *et al* 1990, 388).

Maghaemite is the most important mineral for soil magnetisation, especially in an archaeological context. The crystals have the same structure as magnetite crystals, but in this case only Fe (III) ions are present and there are one ninth less iron atoms than there are present in a magnetite crystal. This means that in each crystal there are a number of vacant sites within the structure, but the structure is made stable due to the presence of other atoms, such as sodium, which fill these vacant sites. As with magnetite the magnetic moments of the ions within a maghaemite crystal are opposed. Although there is still a net magnetic moment, it is slightly less than the magnetic moment possessed by a crystal of magnetite because of the fewer numbers of iron ions present, (Scollar *et al* 1990, 388-90).

If it remains undisturbed, burnt soil appears during excavation as patches of reddish-brown colour. Other features, such as pits and ditches, tend to have higher susceptibilities due to a combination of factors, including the infilling of the features with topsoils, and materials such as magnetically enhanced ashes. However, bioturbation and ploughing tend to disperse these materials, assisted by the downward migration of the small maghaemite particles, which are ultimately deposited on non-magnetic carrier grains (Scollar *et al* 1990, 401). This net downward movement of maghaemite can result in increased susceptibility levels in certain B-horizons, or subsoils, and all of these mechanisms, most importantly leaching and mechanical mixing, known as dilution processes, affect the proportion of magnetic particles present in a volume or area of soil.

Haematite is the most common of the iron oxides and is present in almost all soils, usually in one of its hydrated forms. It is present in concentrations varying from less than 1% up to 10% by weight. It has a rhombohedral structure, quite different from that of magnetite and maghaemite. All of its ions exist in the Fe (III) state, like maghaemite, but in this case all of the sites within the crystal are occupied. The ions have magnetic moments whose directions are equal and opposite, resulting in a very weak permanent magnetisation. The importance of this mineral to magnetic prospection is that it has the potential for conversion into other much more magnetic forms due to human activity or to natural processes (Scollar *et al* 1990, 390-1).

Table 2.9: Magnetic Behaviour of Materials

Type of Magnetism	Electron Shells	Outer Electrons	Magnetic Effects	Measured Magnetism	Examples
Diamagnetic	All full	All paired	Weak, negative magnetic susceptibility. Alter measured fields by $c 1$ part in 10^5 .	Any magnetic effects are due entirely to induced magnetism. Applied field slightly alters electron's orbital motions, and their orbital paths rotate producing a magnetic field opposite to the direction of the applied field (hence -ve susceptibility)	Glass, Cu.
Paramagnetic	Outer shells not full	Some unpaired	Weak positive magnetic susceptibility. Alter measured fields by $c 1$ part in 10^5 .	Individual spins of unpaired electrons produce a magnetic field. Unpaired electron spins rotate in the same direction as an applied field (hence +ve susceptibility). Tend to have single domain grains.	O ₂ , Ti, & some soil minerals.
Paramagnetic: Superparamagnetic (Scollar <i>et al</i> 1990, 395)		Applied to paramagnetic substances that have very small grain size and relatively high magnetic susceptibilities		Tend to have single domain grains	
Paramagnetic: ferromagnetic (G & P 170; Keary & Brookes 1991, 151).		Permanent magnetisation. These materials rarely occur naturally in the Earth's crust and are not relevant to soil magnetism. Increase measured fields locally by a factor of 100+. Tend to have single domain grains, and domain formation involves free electrons. Extremely large enhancement of a total field can occur in a large applied field due to the complete alignment of all the domains in the direction of the applied field). In such cases the material is said to have reached magnetic saturation			Fe, Co, Ni and some of their alloys
Paramagnetic: antiferromagnetic		Coupled in an anti-parallel manner	No external magnetic effect, but defects in the crystal lattice structure cause a small net magnetism: parasitic antiferromagnetism	Equal numbers of electrons lie in each direction, which causes net cancellation of the magnetic moments of each electron dipole. Tend to have single domain grains.	haematite
Paramagnetic: ferrimagnetic (Clark 64; Keary and Brookes 1991, 151)		Coupled in an anti-parallel manner	Relatively weakly magnetic but can produce a strong spontaneous magnetism as well as a high magnetic susceptibility. Permanent magnetisation.	Unequal numbers of electron dipoles in each direction. Grains of these materials contain magnetic domains. Tend to have single domain grains, with a small total magnetic moment due to random arrangement of the domains. Possess much larger MS than multidomain grains because domain size cannot change so stored energy in an applied field is minimised instead by reversal of magnetic direction within the grain	Magnetite, maghemite

2.9 Conclusions

The review of the literature leads to the hypothesis that, although water availability plays a large part in the formation of archaeological crop marks, there are other factors at play too. Of interest is the possibility of there being differences in nutrient element content of the soils constituting the environs of a buried archaeological site. As has been shown, the size of the nutrient pool associated with the most common archaeological remains in the plough zone, cut features such as ditches and pits, is larger when the features create artificially deep soils compared to the natural, undisturbed profile surrounding them. Positive crop marks may represent enhanced growth due to the presence of additional or bigger reserves of nutrient elements because the underlying features are in some way enriched in them. Alternatively there may be a change in physical conditions within the features that make more nutrients available for uptake. These factors may include increased depths of soil, variations in particle size distribution and other textural differences within the features, variable moisture holding capacity and pH. This thesis aims to discover whether there are actual differences in chemical composition in these archaeological features either as a direct result of anthropogenic activity, or indirectly due to the disturbance of the natural soil profile and drainage properties. More specifically, if these differences do exist, can they help to explain not only how crop marks form, but also why the geophysical responses at two of the three case studies (Chapter 5) closely correspond to the differential patterns of crop growth observed.

The literature shows that water availability is an important factor in the initiation and development of differential growth (Jones and Evans, 1975). The assertion that within an individual area the moisture levels in the top 50 mm of soil tend to be uniform (Scollar *et al* 1990) conflicts with the notion that moisture differences cause archaeological crop marks. This returns us to the question of whether the water available to a crop is the only limiting factor in crop mark formation. Where Jones implicates water availability, as a function of SMD and effective soil depth and their combined influence on the available water for the site at Fisherwick (1979, 195-8), there may be other contributory or separate, causes for the development of differential growth. For example, the amount of available water may affect uptake of certain nutrients from solution, rather than actual elemental levels varying across a site.

If water were the only factor in crop mark formation, it leaves the problem of the documented geophysical responses. In many cases the survey results in Clydesdale, for example, reveal a very similar pattern of responses to those visible on aerial photographs. While this can easily be explained in terms of resistivity results, which are traditionally described as responding to the ease with which electrical current can flow through media, and can therefore be related to changes in subsurface moisture content, a similar explanation is not so forthcoming for the results of magnetic survey. The magnetic results suggest that differences other than moisture content are involved. If, however, electromagnetic theory as it can be related to the movement of the soil solution is considered, a link between all three prospection techniques begins to become clear, and the link is related to soil, and more specifically, soil water chemistry.

The solid geology of an area is said to influence its ability to reveal crop marks, although this is brought into doubt by Wilson (1975a, 33-4). He suggests that the drift geology plays a more significant role, and this appears to be a major factor in collecting informative data from geophysical surveys in Scotland (Hanson and Sharpe 2001; Sharpe 1994; Sharpe and Johnson 1998; Banks forthcoming). This biases the investigation toward the more superficial stratigraphic layers and particularly towards the soil itself, as the growing medium for crop plants. The correlation between crop marks and geophysical survey leads to the conclusion that the soil must also strongly influence the latter. The factors indicated in the development of differential growth include soil depth, structure, composition and texture, which determine its nutrient- and water-holding capacity, and the way in which both water and nutrients are available to the growing crop, and the forms in which they exist in the soil.

Soil colour changes, although not directly implicated in growth differences, are ascribed to changes in texture, structure and composition, as can be seen clearly during archaeological excavations. The colour changes recorded in soils are likely to coincide with differences in water content and the presence of ferrous and ferric iron compounds (Scollar 1990, 38). Although this thesis does not consider soil marks, it is clear from this example that soil changes associated with buried archaeological remains can be linked to the chemical state and redox potential of, at a minimum, iron compounds. This gives us an obvious link between soil chemical properties, and resistivity and magnetic survey. Although much emphasis is put upon moisture deficits when considering the causes of differential growth within crops, the main factors recognised by agricultural botanists for

these phenomena are nutrient deficiencies or excesses, which may or may not be due to soil water availability.

Electromagnetic theory was considered in an attempt to link the underlying causes of the three remote sensing techniques considered here, aerial reconnaissance of crop mark sites, magnetic and resistivity survey. This theory has the ability to link the three techniques at an atomic level. Transport of nutrient elements to the sites of active uptake by plants, the root hairs, involves the movement of ions in the soil solution. It is suggested that the presence of these ions and associated electrons, and their movement within the soil solution, is the common link between the three techniques. Changes in concentration of the soil solution are responsible for increased or decreased availability of nutrients from the pool available to growing crops. These changes in concentration also represent changes in the number of free electrons in the solution, therefore producing changes in soil conductivity that are recorded during the resistivity surveys. Finally, the more tenuous and complicated link, which is proven to exist in case studies 1 and 2 (Chapter 5) is developed between crop mark development, resistivity survey and magnetic response by suggesting that electron and ionic movement in the soil solution result in a current flowing in the solution which necessarily has an associated magnetic field that will change according to changes in the soil solution concentration. This interpretation assumes that movement of the ions within the soil water, and within the earth's magnetic field creates an emf within the soil solution, and hence, according to EM theory, an associated magnetic field. The main problem with this hypothesis was to explain how the electrical currents are produced within the soil, unless by an emf as described (D Sanderson pers comm). A possible explanation for the production of currents in soil water is provided by considering electrokinetic flow due to the presence of temperature and osmotic gradients affecting water flow. The suggestion is not that the conventional explanation for magnetic anomalies, as discussed earlier, are incorrect, but that magnetic anomalies also have an input from this electromagnetically induced source due to variations in soil solution concentration. However, as stated earlier this is beyond the scope of this thesis and is offered here as a possibility that requires much more work to resolve or dismiss, not least a consideration of the magnitude of the charges capable of being generated and that of their associated magnetic fields, and whether these quantities are practically measurable by the instruments in common use. This thesis will continue to investigate the correlations between the techniques on the basis of soil chemistry, taking the main cause of the anomalies to be changing elemental concentrations of, for example iron as a significant contributor to all three anomaly types.

In the next chapter, the methodology used to investigate these hypotheses is established. During a series of experiments that involved the growth of barley plants under glasshouse conditions, there was a qualitative examination of the effects of some of the factors associated with the development of crop marks. Next, some of the plants, together with soils from the three case studies, were analysed for a suite of elements to assess the variations in elemental levels depending on archaeological context and cultural conditions. The results of this experimental work are presented in Chapter 6, following on from the results of the remotely gathered data, presented in Chapter 5. The whole is brought together in a concluding chapter (Chapter 7), which discusses the probable causes of crop marks and geophysical anomalies based upon the theoretical and experimental work undertaken.

Chapter 3: Methodologies

3.1 Introduction

This chapter describes the methods used to carry out the experimental and survey work involved in the thesis. From the examination of the principles and theoretical basis of crop mark formation undertaken in Chapter 2, three factors become clear. First, that crop marks forming at the sites of archaeological remains are the result of differential growth of the overlying plants. Second, as these patterns are also recorded in the geophysical plots from two of the Case Studies (Chapter 5), the magnetic data particularly imply that crop mark formation cannot be due solely to differences in soil moisture content, but also arise due to a factor that also affects the magnetic signal. Third, it is clear that an investigation into the links between geophysical data and crop mark information is necessary to advance the understanding of both types of response and of the nature of the underlying remains themselves. This prompted a series of investigations that aimed to address the questions arising from the first two factors, in an attempt to satisfactorily advance the third. In the course of this research, soils relating to the crop marks and geophysical responses from the Case Studies, and plant material grown in them, were examined. The investigations commenced with the examination of aerial photographs of the crop marks at each site, followed by geophysical survey. Next, soil samples were taken from the sites. Depending on the size of the samples, details of which are given below and in Chapter 5, the samples were subject to a variety of investigations. These ranged from a qualitative description of soil characteristics, through to use in experimental growth of barley and manipulation of cultural conditions under a controlled, glasshouse environment. The aim of this work was to assess the role of water availability and other soil factors in the development of differential growth such as that seen in a crop mark. This primary work then facilitated an investigation into the chemical differences present in the archaeological soils and in plants that had been subjected to differential water availability. Inductively coupled plasma- mass spectrometry (ICP-MS) was used to analyse their chemical compositions. Analysis of plant material as opposed to simply analysing the soils had two objectives. First, it allowed an appreciation of the development of differential growth in response to altered cultural conditions, and perhaps more importantly, because analysis of plant material provides a more sensitive indicator of nutrient status than can be achieved by analysing the soils directly, a more subtle examination of the availability of nutrient elements could be effected via the plants.

This chapter addresses each of the methodologies in turn. As all aerial photography of the Case Studies was available prior to the start of the UCVLP and this experimental work, methodological discussion of aerial reconnaissance contributions is limited to a description of the rectification and subsequent use of the photography. Geophysical applications and details of survey logistics follow, with information on the addition of these remotely sensed sources to a project in ArcView GIS. Next, soil- and plant-based work is described. This encompasses the glasshouse experiments which examined the growth of barley plants under controlled conditions, and the qualitative and quantitative assessment of the effects of differing cultural (in an agricultural sense) regimes upon them, and the analytical techniques applied to soil and plant samples.

3.2 How the Aerial Photography is Used

The aerial photography used in this study comes from three sources; from the private collection of Professor W S Hanson, GUAD, from Cambridge University Collection of Aerial Photographs (CUCAP) sources held in the National Monuments Record for Scotland (NMRS), and from aerial reconnaissance by RCAHMS staff.

With the exception of the CUCAP photographs, which are all panchromatic prints, the sites are also usually photographed using colour negative, and occasionally colour print film. As all of the Case Studies are recorded as plough-truncated crop marks, all of the photography consulted was taken during the summer months when the fields had full vegetation cover. This is distinct from having crop cover, as Case Study 3 produces differential growth in pasture, as does Case Study 1, although aerial photographs of the latter tend to be taken when it has cereal crop cover. This is discussed in more detail in Chapter 5. All of the sites with sufficient information recorded on the photographs were rectified originally for the UCVLP and then utilised in this study. Sufficient information is defined as not only the appearance of coherent patterns in the crop, but also enough control points to allow the photograph to be rectified (Wilson 2000, 229). As is often the case, photographs that revealed most about the sites did not necessarily have good control information. Consequently, the best photograph often represents a compromise between these two essential requirements. The rectification program Aerial 4.20, a DOS based program, was used to produce corrected plans of the three sites. This program allows digitised line plans of the archaeological features on the photographs to be mapped in their geographically

corrected positions, thus removing any displacement caused by the oblique angle of the photography. Transcriptions represent a second stage of interpretation of the features, the first stage being the photographer recognising and recording of the remains from the air.

In order to rectify a photograph of a site in Aerial 4.20 there must be at least five control points visible on it. These fixed and accurately identifiable features are recognisable on both the photograph and the 1:2,500 scale OS map that covers the location of the site. Good examples of reliable control points include field boundary junctions, corners of buildings and road junctions. The availability of adequate control points can be problematic for areas such as the Lothians, where modern agricultural practice has moved increasingly towards large-scale intensive arable farming. The result is that wholesale removal of field boundaries to consolidate numerous smaller fields into one large area for cereal production is the norm. Consequently, although this may increase the chance of recording crop marks (because site destruction by ploughing is increasing), there is less chance of producing accurate plans of the sites because any control points once present have been removed. This has implications for resource management. Fortunately for the archaeological remains and the aerial archaeologist this has not tended to happen in Upper Clydesdale, and during the UCVLP transcription programme only a handful of sites lacked the necessary control for rectification. As shall be seen in Chapter 5 however, at Case Study 1, there has been a change in the mapped field boundaries. Several smaller fields, one of which entirely contained the enclosure, now exist as one very large one, and this did have an impact on the rectification of aerial photographs. Where control is lacking from photographs, perhaps because the photographer has framed the site tightly to record detail, it is possible to include this detail in a final interpretation of the aerial information. This can be accomplished with the aid of a completed transcription from a photograph with good control, but less informative crop marks, which is used as a base map rather than the OS base. In this way it is possible to plot the maximum detail about the site from several photographs. Additionally, for sites with very poor control it is often possible to produce an accurately rectified plan using control points constructed from a Mobius network. Some of the photographs used in the production of the plan of Case Study 3 had Mobius networks constructed for them before the transcription. In most of the photographs there was a lack of control points along the whole western side of the site. Again, this is discussed fully in Chapter 5.

Once transcribed, the files produced in Aerial 4.20 (.dat files) were converted into standard data exchange (.dxf) files, which could then be opened directly in an ArcView project. From

here the transcriptions can be viewed in relation to each other in their geographically correct positions, and also overlain with site information gathered from other sources.

The current consensus is to use programs such as Airphoto and Aerial 5, rather than the older Aerial 4.20. These later programs rectify aerial photographs by stretching a scanned image until it accurately fits the base map, pulling the site into its true ground position as it does this. Despite the availability of these later versions of Aerial, and of other Windows-based aerial rectification programs after the original transcriptions were made, the earlier program and transcriptions produced from it have continued to be used. The accuracy of the transcriptions has been proven in the field on several occasions (Hanson and Sharpe in prep; G Barclay pers comm). Additionally, the line drawings produced are similar to and good for comparison with the interpretative plots produced from the geophysical survey results. In addition, there is the question of interpretation to consider. The later programs take away the subjective interpretative aspect of rectification, which is a positive for archiving photographs and making them available as a research tool (although an interpretative overlay can also be produced in these applications). The interpretative step involved in rectification in Aerial 4.20 is essential to the comparative analysis of different remotely sensed datasets in this study.

3.3 Geophysical Survey Methods

The two most commonly used survey techniques, magnetometry and electrical resistivity, were applied to the Case Studies. Geoscan Research Ltd made both instrument types used in the surveys as well as the data processing software into which the survey data were downloaded, Geoplot v.3 for Windows.

Data was also gathered using Magnetic Susceptibility (MS), another useful prospecting technique. Measurements of MS can be made both in the field and in the laboratory, using a field or laboratory coil respectively. As this study made use of laboratory rather than field measurements of soils and plant materials, the methodology is discussed alongside the other laboratory techniques in Section 3.4. The theoretical basis for my research is detailed in Chapter 2, leaving only the details of how data were collected and used to be described in this chapter.

The Site Surveys

The surveys discussed in this thesis were undertaken during the UCVLP (see Chapter 4). As part of a landscape investigation, the geophysical survey component of the project covered a lot of ground with both geophysical techniques (Hanson and Sharpe in prep). Recent work on sampling density for survey suggests that a sampling interval of 1.0 m is satisfactory for most sites (Gaffney and Gater 2003, 95; Hanson and Sharpe in prep). Despite earlier work being carried out which suggests an optimal sampling density of 0.25 m or 1.0 m by 0.5 m maximum (Clark 1991, 81; David 1995, 17), small-scale trials undertaken by the author in Westray (1998, unpublished) to determine whether more information can be gleaned from a site when a smaller sampling interval is used proved that this is generally not the case. At Quoygrew, Westray, it was possible to detect a house with central hearth and external midden at a sampling interval of 1.0 m. This interpretation was proved first by augur survey (Iain Simpson, Stirling University) and later by excavation (Dr J Barrett pers comm), and additional survey at a 0.5 m sampling density did not add to the information gathered in the original survey. This does not of course rule out the usefulness of small-scale survey and, indeed, it has proved to be very valuable at one of the sites examined for this thesis, at Chesterhall Parks enclosures (Case Study 3, Chapter 5). At Stanton Drew in southern England an astounding amount of detail was gleaned using small sampling intervals. A fluxgate gradiometer survey at a sampling interval of 0.25 m by 0.25 m was followed by survey with a caesium vapour instrument at a sampling density of 0.5 by 0.125 m at the henge monument. The latter survey managed to resolve individual postholes clearly, and almost precludes the need for invasive investigation at the site (Gaffney and Gater 2003, 69). However, the need to cover much ground, and the success in general of the 1.0 m sampling interval in detecting and delimiting individual features and sites, influenced the decision to standardise survey design to this interval for both the UCVLP work and for this thesis.

For each of the surveys the methodology was as follows: a 20 m x 20 m survey grid was established over the field, each grid covering the enclosures and a surrounding, apparently 'blank' area. This aimed to sample the 'background' readings relative to enhancements developed due to the presence of the site. The survey then commenced using sampling and traverse intervals of 1.0 m for both survey types. Data were transferred into Geoplot v3 at the end of each day. Keeping the starting position and the direction of traverse identical for each individual grid square allowed the data to be joined to form a composite plot of all the data in the whole survey area. In this way, a geophysical 'picture' of each site was produced, which depicted areas of enhanced or depressed resistivity or magnetic readings.

Magnetic Prospection

Set up of the survey grids and the instruments was accomplished in accordance with best practice (Geoscan instrument manuals provide full detail; see also David 1995, 17-18; Clark 1990, 69). To gather highest quality data, the instrument was always zeroed in the direction of survey traverse, rather than in the north direction. Setting the instrument to a relative site zero ensures that all data for that particular site are collected relative to this same starting reading. This tends to produce a more consistent background intensity for each grid, and thus to assist in seamlessly combining all the data to produce the composite survey plot, reducing the need to process out edge effects or artificially match grid backgrounds. This was particularly important for the UCVLP surveys as they were used as training surveys and as such there were often three of each of the instruments working at each site.

Magnetic survey proceeded using parallel traverse mode. After each grid had been surveyed, the operator logged the amount of drift that had occurred from the initial zero reading and the balance, and if necessary alignment, of the fluxgates was checked and the instrument re-zeroed before returning to survey the next grid. At the end of each day the data gathered was transferred to a laptop computer into Geoplot v.3.0. Data was checked to ensure it was not corrupted and, after a composite had been created, it was used to inform and direct the next day's survey strategy. This ensured the detection of features likely to allow a fuller interpretation of the site to be maximised, their extents to be defined, and limited survey time to be fully utilised.

Electrical Resistivity

The survey methods for the resistivity meters were much the same as those described for the gradiometer surveys. However, survey was undertaken in a 'zigzag' pattern. For all of the surveys, the RM15 was used in conjunction with a frame supporting a twin electrode configuration. The inter-electrode separation was 0.5 m, biasing the measurement point to around the same depth below ground as the spacing. At sites where more than one instrument was in use, the background resistances for each instrument were matched at the start of survey. This was accomplished by acquiring a starting resistance value from the same set of fixed electrodes for each of the instruments used at the site, before leapfrogging them to their individual grid start positions using their own dedicated electrodes. This methodology was seen to work well with little need for edge matching when the data from the individual instruments was combined in the site composite.

Data Processing and Interpretation

At the end of each day data were downloaded from the instruments and inspected for integrity and to allow the next day of survey to be planned. Interpretation was left until the full survey was complete. Generally the data was of good quality and needed very little processing. This was mainly confined to elimination of edge effects, mainly in the magnetic data, and of spurious high readings, producing narrow, high frequency spikes, caused by the presence of metal in the magnetic data, and by poor electrode contact in the resistivity data. Beyond this, use of high- and low-pass filters to enhance archaeological features at the expense of geological and soil-derived signals was the main processing step. Clipping and interpolation of the data, together with the application of different colour palettes and relief plots completed the data treatment for the Case Studies (Geoscan Research Ltd 2000).

3.4 Soil and Plant Analyses

A series of growth experiments were undertaken, all of which are described here, and the results discussed in Chapter 6. The experimental plant-based work involved the growth of spring barley under the controlled conditions of a glasshouse environment in pots containing either compost or soils taken from the Case Studies. The aims of this work were to investigate more closely the conditions that cause differential growth, and so presumably archaeological crop marks, to appear in barley. The data collected from this work ranged from a qualitative record of the growth habits of plants subjected to differing water regimes, through to a full quantitative, analytical assessment of the nutrient status of the plants following harvest.

Collection of Archaeologically Significant Soils

The exact location of the soil samples is discussed on an individual site basis in Chapter 5, but involved either point collection from within the geophysical survey grids using a corkscrew auger (Sites 1 and 2), or bulk sample collection from individual archaeological contexts during trial excavations (Sites 1 and 3). The method and methodology of collection is discussed here. To standardise results, and to remove any differences in soil chemical composition due to surface deposition or contamination, all augured samples used for analysis were taken from 10 – 20 cm below the ground surface. Samples from deeper than this (c.30 cm) were also collected in the field, but ultimately were not used due to variable

soil depths preventing samples from all points in the grids being available. Bulk samples of soils were not taken as sample collection was designed to be directly comparable to that collected geophysically and aerially, that is no absolute off-site background values were known for any of the three prospection techniques. Geophysical survey data are relative as opposed to absolute and are not compared against an off-site background datum. Similarly aerial prospection is site specific, with oblique aerial reconnaissance data not routinely providing a sample of the landscape in general, merely recording what is archaeologically significant at the time of the reconnaissance flight. In the same way came the decision, coupled with space and financial restraints, to make the soils and consequently plant data for individual Case Studies a relative examination of areas of enhancement or depletion of certain nutrient elements and other physical properties (ICRCL 1987; Entwistle *et al* in prep; Wilson *et al* in prep).

Barley Growth Experiments

Much work has been carried out on the response of plants to nutrient and water levels (Marschner 1995; Larcher 1995; Bould *et al* 1983). However, this has not surprisingly focused largely on the need to produce optimum yields from food crops. This involves large-scale study as opposed to the information required to understand the very small-scale responses of individual crop plants to buried archaeological remains. Additionally, being concerned with maximising yields, the study of agricultural crop production tends to focus on the effects of nutrient deficiencies and inadequacies in irrigation requirements. The appearance of archaeological crop marks suggests the reverse of this situation, that positive crop marks are indicators of excesses of these cultural resources. Therefore, while this study can borrow from the range of analytical techniques employed in the study of crop production systems, it is rarely able to borrow from the results and conclusions of such studies. It has proved impossible, for example, to find abundant literature on the effects upon growth of excesses of nutrients (Bould *et al* 1983, 97-100), although excesses of soil water are an exception to this (Larcher 1995, 375-8).

To allow the circumstances under which crop marks develop in barley to be more closely investigated, a series of small-scale experiments were carried out under the controlled conditions of a glasshouse. The decision to undertake a glasshouse investigation, rather than a field-based one, was partly logistical. Assuming that field and weather conditions favourable for crop mark formation arose that coincided not only with a suitable crop being

in the field but also with the time available to complete this thesis, there remained the difficulty of persuading farmers to allow the removal of plants and underlying soils from the mature crop for analysis. Even if these factors could be assured, there was then the problem of accounting for such variables as soil depth and other properties, fertiliser loads, precipitation and plant density, to name but a few that individual field grown crop plants experience. Because plant maturation and soil processes are complicated enough, the more variables that could be eliminated, the better informed the study would be.

The most important factors for plant growth are adequate water, heat, light, lack of pressure due to competition for space or nutrients, and an environment free of pests and pathogens. In the glasshouse environment not only can these criteria be controlled, but they can also be standardised. This allows certain parameters to be varied, with all others remaining constant, to enable their effects on growth to be assessed, a methodology upon which all such comparative experimental work is based. Specifically it can be applied to the archaeological questions posed regarding the formation of crop marks. Implicitly, variations in water content and soil depth are assumed to be due to the presence of buried archaeological remains. Can availability of water affect the growth of spring barley in a way that would be expected based on observations during aerial reconnaissance for crop mark sites? Does an adequacy of water produce lush, dense, darker green growth habit, compared to the paler green, less dense growth of plants deprived of optimum water requirements, for example those growing over shallowly buried building remains? Is water supply the sole factor or does a change in availability during different growth stages and the timing of that change have an effect too? Does topsoil depth play a part in the equation? Does availability of nutrients play a significant part in the recorded growth differences, and if so are the differences associated with the water availability or are they anthropogenic in origin? All of these questions are addressed in the experimental work.

This ability to control the growth environment, however, does give an artificial slant to the results. For example, it is possible that conclusions drawn from glasshouse-scale experimental work cannot ultimately be applied to field situations, and one must be mindful of the constraints as well as the advantages offered in the form of environmental control. The most obvious drawback to this trial is the fact that there is a complete absence of underlying archaeology below the growing plants. This means that any growth differences detected cannot be ascribed to archaeological features themselves, although in many cases the archaeological soils *are* the only features present, filling, for example, remains of ditches.

This is particularly the case, however, in the experiments involving growth in proprietary compost detailed below. This work is important though as it allows an assessment of how cultural factors alone influence growth habits. If the results show that the growth habits mimic those recorded in crop marks exactly, it will effectively prove that water availability is the most significant factor in crop mark formation. Either way, the information from this experimental work can be used as a baseline for the assessment of the contribution of the archaeological input to crop mark appearance explored in the remaining two experiments (see Table 3.1). For example, the difference in growth habit due to a change in soil depth may be further enhanced if the depth change relates to buried archaeological remains that are also contributing to a localised soil chemistry change.

Partly to address the problem of simulating archaeological remains outlined above, some of the experimental work involves the growth of spring barley in soils taken from the Case Studies. Although the problem of the physical absence of the site features remains, this work seeks to address whether there is a chemical enhancement of soils at an archaeological site that has an effect on the growth habit of crops. These experiments, then, implicitly test the hypothesis that growth differences are due to the presence of archaeological remains in that this causes localised changes in soil chemistry, and that these changes are detected by remote sensing techniques. If soil moisture, soil depth or the physical presence of archaeological features is solely or jointly responsible for the production of crop marks, the simple act of isolating the soils from the remains, the vagaries of the Scottish weather, and of standardising soil depths, should remove any growth differences in these experiments. Even though in many cases the soils are the features, as mentioned, standardising the volume of feature along with the remaining cultural (in the plant growth sense) factors should be enough to determine whether it is these physical differences or changes in elemental concentrations in the different features that are responsible for altered responses at the sites of buried archaeological remains.

Spring barley seed collected in 1999 (*Hordeum sp.* cv. Chariot) was kindly provided by Dr Tim Wassail of the Scottish Agricultural College (SAC, Auchincruive, Ayrshire). These seeds were grown under a variety of controlled cultural conditions and in a variety of media during a series of 5 sets of experiments. The experiments were set up in a glasshouse at Garscube Estate, University of Glasgow, on 9 May 2000. For experiments 2 to 4 (Table 3.1) each plant pot, which was to be subject to a specific treatment, was randomly numbered by pulling numbers from a hat and assigning them consecutively to each individual treatment

listed, thus randomising the replicates and treatment types within each individual experiment (see for example Table 3.2). The randomised pots of barley were then arranged on the glasshouse bench in numerical order, to facilitate easy application of the different watering regimes, and recording of development. Randomising plants in this way decreases the probability of producing significant pattern of growth within one treatment which are due to, for example small differences in temperature or light levels. In the sheltered environment of the glasshouse it is possible to control the air temperature (especially the minimum temperature) and to record the daily fluctuations, and glasshouse design permits a maximum amount of daylight to reach the growing plants. However, differences in both of these factors arise because of the presence of glazing bars and the position of heaters and ventilation. Light levels and air circulation between individual plants also change across the benching due to plant density, hence the need to randomise. In addition to randomising the pots within the experimental groups, the plants were systematically re-arranged on a weekly basis. In this way any growth differences caused by environmental factors within the glasshouse should theoretically be evened out over the growth period. Experiment 1 comprised three plant pot saucers, and Experiment 5 nine large black rubbish bins, so the small and large sizes of the containers respectively precluded them from being randomised in this way. This is seen as slightly problematic for Experiment 5 for reasons discussed below.

Table 3.1: Summary of Experimental Plant Growth Work

Experiment 1	Germination test
Experiment 2	Growth of spring barley in archaeological soils from Case Study 2
Experiment 3	Growth of spring barley in archaeological soils from Case Study 1 under differing watering regimes
Experiment 4	Water availability and its effects on the growth and development of compost-grown spring barley.
Experiment 5	Effects of soil depth variations and water availability on the growth and development of compost-grown spring barley

Experiment 1: Germination Rest

The germination experiment was set up on 15 May 2000. This is a standard horticultural test to determine the percentage germination of the seed batch. This technique allows the viability of the seeds to be determined with all factors other than heat, moisture and light removed. Variations in germination rates due to cultural differences were anticipated in the experimental work. Therefore, it was necessary to determine the viability of the seed batch

to provide a control against which to compare germination differences in the remaining experiments.

100 barley seeds were sown onto filter papers draped over the upturned bases of petri dishes in plant saucers (Plate 3.1) to provide a moist growing platform with a surrounding reservoir of water to prevent the seeds from becoming desiccated. The saucers were covered over with polythene to maintain humidity and speed germination. After one week the number of seeds germinated was counted, and this gave a percentage germination success for the seed batch.

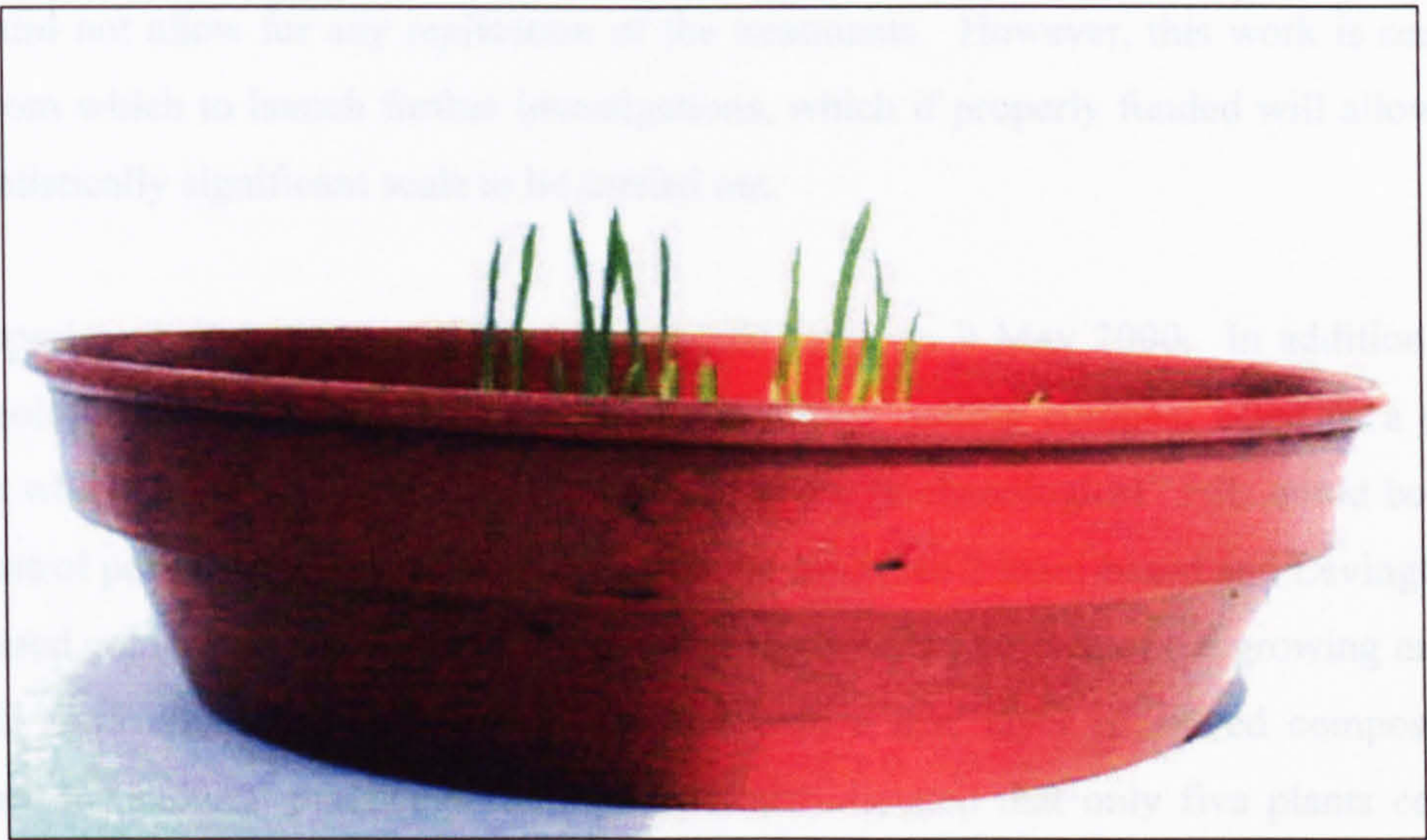


Plate 3.1:

The germination test: One of the three saucers used in the germination test, showing growing barley plants with the first true leaves emerging.

Experiment 2: Growth of Spring Barley in Archaeological Soils

The aim of this experiment was to determine whether growth comparative to that seen in archaeological crop marks could be produced in plants grown under glasshouse conditions, using soils that are known to produce differential growth in the field. For this purpose augured soils from Case Study 2 were used (Burnfoot Farm, see Chapter 5). The samples were taken in April 1999 in a grid pattern from an area of the field where both the FM36 and the RM15 (Figure 5.10) had recorded geophysical anomalies. At each point three samples were taken with a corkscrew auger at a depth of 10-20 cm below the ground surface and a

second set of three samples were taken from 20-30 cm below the ground surface. At some of the sample points the 20-30 cm samples are absent as the soils were too shallow and the auger struck drift or solid geology. Where successfully secured, the three samples from the same depth range were bulked together, and all samples were stored frozen until May 2000. After defrosting, a sub-sample of each was removed (c.30 g) for laboratory analysis as detailed below. The remaining sample was used in Experiment 2 (Table 3.2).

The experimental design for the growth experiments using soils from this site was limited by the small amount of soil contained in each sample. Sample size was constrained because the farmer, Mr D Russell, was not keen for the field to be disturbed in any way. Despite the replicated sampling regime, there was only enough soil per sample to fill a 9 cm plant pot, which did not allow for any replication of the treatments. However, this work is seen as a pilot from which to launch further investigations, which if properly funded will allow work on a statistically significant scale to be carried out.

The experiment was set up and the barley seeds sown on 9 May 2000. In addition to the 'archaeological' soils, a pot set up using horticultural potting compost acted as a control against which comparisons of the plants grown in the 'archaeological' soils could be made. The control pot contained a 50/50 mixture of John Innes No 2 loam-based and Levington M3 peat-based composts. All seeds were sown directly onto the surface of the growing media to emulate field conditions, rather than covered with a thin layer of sieved compost as is standard horticultural practice. The small pot size dictated that only five plants could be grown on per pot, though an average of ten seeds was sown in each.

Germination success was noted, and once the first true leaves had emerged plants were thinned out or pots augmented by transplanting plants from the germination experiment to ensure that each pot contained five barley plants. Growth conditions were maintained at optimum, and soil depth, water requirements, temperature, crop density and light levels were standardised as much as was possible (Plate 3.2). The glasshouses were visited daily for the duration of the experimental work, and all of the Experiment 2 pots were watered as required from sowing to completion of the work. The watering regime was standardised as far as was possible, although requirements were found to vary slightly with each soil sample.

Table 3.2: Soil Sample Location for Case Study 2

<i>Sample Co-ordinate</i>	<i>Sample Depth</i>	<i>Pot No</i>
00, 00	20 cm	31
00, 00	30 cm	27
00, 10	20 cm	6
00, 10	30 cm	16
00, 15	20 cm	32
00, 15	30 cm	4
00, 20	20 cm	15
00, 20	30 cm	40
00, 05	20 cm	24
00, 05	20 cm	23
10, 10	20 cm	1
10, 10	30 cm	26
20, 00	20 cm	3
20, 10	10 cm	12
20, 10	20 cm	28
20, 10	30 cm	38
20, 20	10 cm	8
20, 20	20 cm	7
30, 00	10 cm	30
30, 00	20 cm	36
30, 10	10 cm	2
30, 10	20 cm	33
30, 20	20 cm	37
30, 20	30 cm	17
40, 00	20 cm	25
40, 00	30 cm	22
40, 10	20 cm	41
40, 10	30 cm	18
40, 20	20 cm	34
40, 20	30 cm	29
50, 00	20 cm	43
50, 00	30 cm	5
50, 10	20 cm	11
50, 10	30 cm	19
50, 20	20 cm	13
50, 20	30 cm	39
60, 00	20 cm	10
60, 00	30 cm	14
60, 10	20 cm	20
60, 10	30 cm	21
60, 20	20 cm	35
60, 20	30 cm	42
Control	Control	Control

Within a short time it became clear that the small soil volume would not support this number of plants, and so they were thinned again to leave first three and then one plant per pot. Once it became clear that all available nutrients had been exhausted in the soils, the plants were harvested. All top growth was removed by cutting the foliage at soil level just above the seed coat. The aerial portion of the plant material was then weighed and, much to the amusement of other members of the department, photocopied to allow an analysis of leaf area index (LAI) to be carried out at a later date. Finally the plant material was put into paper envelopes and dried in a drying cabinet at an average temperature of 80C for around 24 hours.

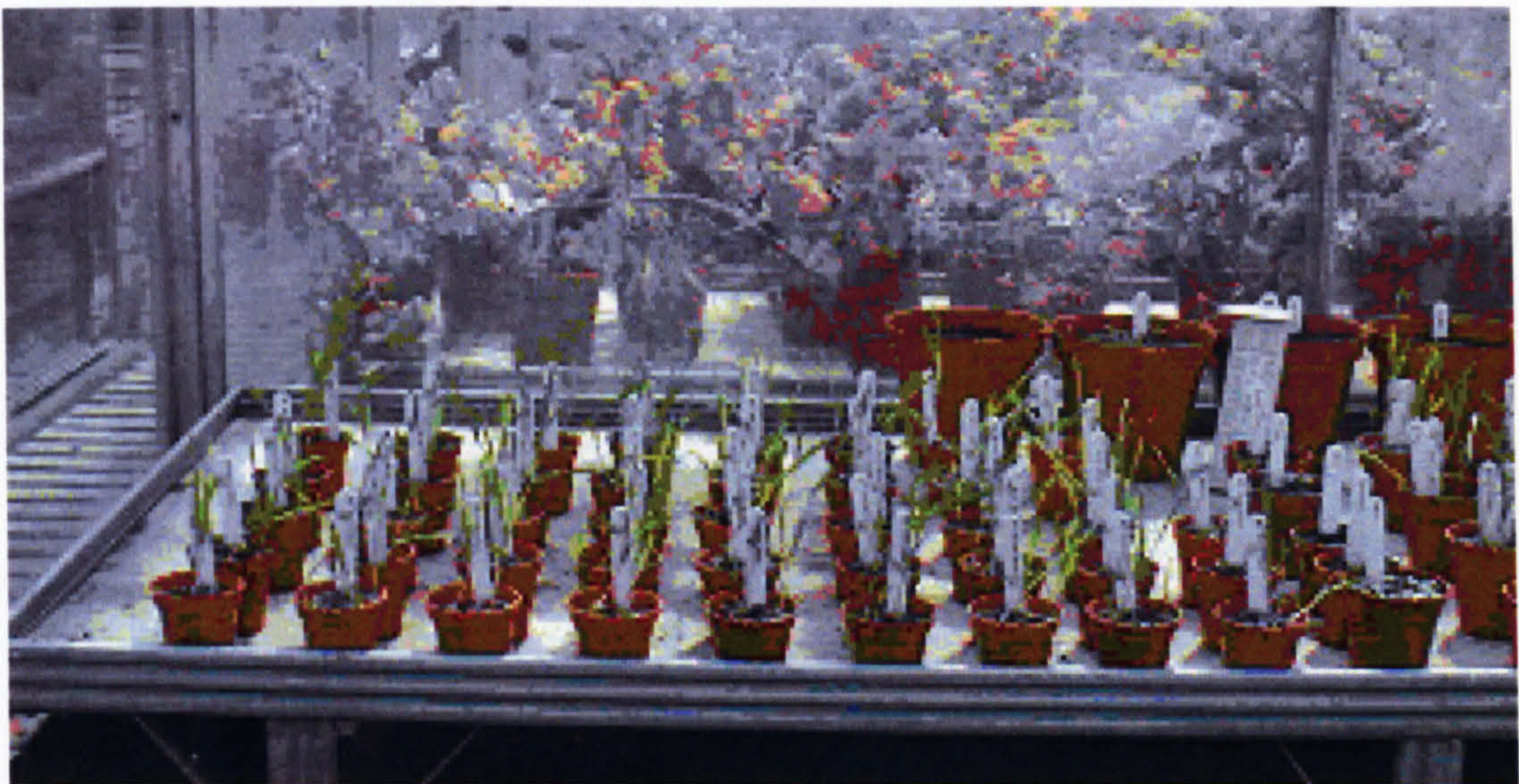


Plate 3.2:

Experiment 2: Barley growing in Case Study 2 soils.

The soils and the dried plant remains from this experiment were analysed for their elemental concentrations using ICP-MS. The details of this phase of experimental work are given below. From the point that the radical had emerged, all details of the growth of the plants in the individual pots were closely recorded. Factors noted included the speed of development of the seedlings, the percentage germination per pot, and the number of leaves and tillers that developed. At harvest the plants from this and the remaining three experiments were weighed and measured, the number of tillers and flowering heads, where applicable, were recorded.

Experiment 3: Growth of Spring Barley in Archaeological Soils Under Differing Watering Regimes

Soils from Case Study 1 (Craigie Burn enclosure) were used in this experiment. Because a small amount of test pitting had been undertaken at this site, there was enough soil to allow three pots from each context sampled during excavation to be set up. The cultural details of this experiment are the same as the set up for Experiment 2, although it was possible to use 9 cm pots for this group (Plate 3.3). Although augured samples were also taken from the geophysical survey grid covering the Craigie Burn enclosure, these were not used in the growth experiments, but were analysed for elemental composition. The analysis of both groups should allow a comparison of nutrient status at a constant depth (augured samples) relative to that for the specific features that comprise the site. This will allow a discussion of how the underlying features affect the rooting zone of the crop plants.



Plate 3.3:

Experiment 3 underway in the glasshouse.

The soils from each context were this time used to fill three plant pots. The pots were again randomly numbered and set out on the glasshouse bench in numerical order. As with experiment 2, a control pot was set up for each treatment, using the 1:1 mix of John Innes No 2 and Levington M3 described above. Ten barley seeds were sown onto the surface of the growing medium in each pot, on 9 May 2000. The pots in this experiment were also moved on the glasshouse bench weekly, as described and for the same reasons as those in Experiment 2.

Unlike Experiment 2, the watering requirements of this group of plants was standardised and the amounts of water given to each pot recorded. The plants were subject to three watering regimes from the same growth stage. One third of all of the plants were grown under optimum moisture levels, one third under drought conditions, and the remaining third under waterlogged conditions. Each of the three pots of soil from each context was assigned to either group W (wet), D (dry) or O (optimum), based on the three watering regimes to be applied to the pots (Table 3.3). Group W would be kept excessively wet to the point of waterlogging, Group D would be kept dry without the plants reaching permanent wilting point (PWP) and Group O would be given the optimum level of water for healthy growth. By 11 May 2000, again 2 days after sowing, the seeds had begun to germinate, and the watering regimes were started on 12 May 2000. Initially this entailed watering the W group daily, the O group as was thought necessary, and not watering the D group to allow for the soils to dry out to a level where minimal watering could be applied.

Once the three treatments were in place a more standardised watering regime was applied, with the same amount of water given to all of the pots in each of the three groups, according to the regime. This was considered the best methodology to simulate field conditions in that if one droughted pot was watered, the field equivalent would be light rain, and so all of the contexts would receive water. The watering regimes were planned to be quantitative, using a soil moisture meter to measure the moisture levels in each individual pot and allow a measurable difference to develop between each treatment. However, the soil moisture meter that was available within the limited budget proved to be inferior and not a reliable indicator of soil moisture conditions and was abandoned after a couple of trial batch measurements. Instead the watering regime comprised measured application of water. The final standardised regime was started on 17 May 2000, after the group D pots had dried out relative to the group O ones.

Table 3.3: Archaeological Contexts of Case Study 1 Soils Used in Experiment 3

<i>Pot No & Treatment</i>	<i>Context No</i>	<i>Feature Type</i>
4O; 35D; 43W	Controls	Compost
1D	SS1006	Internal Ditch
2W	SS2002	Natural
3D	SS2001	Topsoil
5W	SS1001	Topsoil
6D	SS2007	Earlier medial ditch below 2003
7D	SS3001	Topsoil
8W	SS2001	Topsoil
9W	SS2003	Inner Medial Ditch
9aD	SS2006	Natural
10W	SS1006	Internal Ditch
11O	SS3003	Natural
11aW	SS2006	Natural
12D	SS3003	Natural
13W	SS1003	Internal Ditch
14D	SS1001	Topsoil
15O	SS1006	Internal Ditch
16W	SS3003	Natural
17O	SS1001	Topsoil
18O	SS3005	Outer medial Ditch
19D	SS3005	Outer medial Ditch
20O	SS3001	Topsoil
21D	SS1005	Natural
22O	SS2005	Inner Medial Ditch
23D	SS1002	Natural
24W	SS1002	Natural
25O	SS2007	Earlier medial ditch below 2003
26W	SS3004	Natural
27D	SS2005	Inner Medial Ditch
28W	SS1005	Natural
29D	SS2003	Inner Medial Ditch
30O	SS1002	Natural
31D	SS3002	Outer Medial Ditch
32W	SS3005	Outer medial Ditch
33O	SS2003	Inner Medial Ditch
34W	SS2007	Earlier medial ditch below 2003
36O	SS2001	Topsoil
37O	SS3004	Natural
38W	SS2005	Inner Medial Ditch
39D	SS1003	Internal Ditch
40W	SS3002	Outer medial Ditch
41W	SS3001	Topsoil
42O	SS3002	Outer medial Ditch
44O	SS1005	Natural
45D	SS2002	Natural
46O	SS1003	Internal Ditch
47D	SS3004	Natural
48O	SS2002	Natural
49O	SS2006	Natural

D: droughted; W: waterlogged; O: optimal watering regime

As with the Experiment 2 plants, grown in the augured Burnfoot soils, the plants growing in the Craigie soils began to show symptoms of nutrient deficiency around 26 May 2000. This was despite having thinned out the plants to leave five plants per pot. Instead of harvesting the plants at this stage, as in experiment 2, the Craigie soils were given a liquid feed of Bio Plant food on 6 June 2000, to allow the plants to continue growing for longer. The fertiliser application consisted of the recommended dose of 15 ml Bio Plant Food to each Gallon of water, and each pot was watered with 200 ml of the solution, which is the standard amount of water given per application when watering normally. The liquid fertilizer provides a 10.6:4.4:1.7 ratio of N:P:K, the convention for expressing major nutrient applications in horticultural and agricultural crop management terms. This is likely to be a similar regime to that applied agriculturally to crops. This gave the opportunity to examine the growth of the plants before and after the addition of fertiliser, which has been discussed with reference to crop mark appearance by several workers (see Chapter 2). Applying fertiliser does however bring in to question the relevance of applying chemical analysis to the plants and soils used in this experiment. This can be justified with reference to the field situation where conversation with the farmer at the farm on which the site lays, revealed that a slow release fertiliser is applied to the soil at Craigie each time it is ploughed. Additionally, as will be discussed in the results section (Chapter 6), N was not analysed in any of the samples due to financial constraints, and for the plant analyses undertaken, unfortunately P concentrations were disregarded due to consistent errors in the data assumed to be due to contamination during digestion or preparation for analysis.

By 13 June 2000, some of the plants had begun to produce flower heads. These were allowed to continue to develop until 27 June 2000, when the plants were harvested. It must be noted that despite many of the plants producing flowers, the growth of in general of the plants was stunted due to the small size of the pots that they were grown in. At the time that the plants were harvested there was little difference in the colour of the living aerial portion of the barley plants. The main differences that were noted between the treatments included differences in height, number of tillers, number of dead leaves and the development of the flower heads and seeds (Chapter 6). The most advanced plants at harvest were those that had developed tillers and/or seeds, and in the latter case the seeds were formed but not ripe.

As with the Burnfoot plants, the Craigie plants were harvested by cutting the aerial portion of the plant above the seed coat, weighing, drying and re-weighing the material and storing it ready for further analysis.

Experiment 4: Water Availability and its effects on the Growth and Development of Compost-Grown Spring Barley

This experimental work was aimed at reproducing the effects seen from the air when a crop mark is visible. Here the plants were subject to three watering regimes from various stages of growth to attempt to test the commonly held hypothesis that water availability is the primary cause of the differential growth seen in crop marks in spring barley.

One third of all of the plants were subject to optimum moisture levels, one third to drought conditions, and the remaining third to waterlogged conditions, as in Experiment 3. In this experiment however, in an attempt to standardise all cultural conditions except for the watering regime, soil depth, texture, structure, and nutrient content were standardised by the use of proprietary composts. The plants were grown in 18 cm pots to prevent nutrient exhaustion during growth. The treatments were divided into two batches, the first being subject to the differential watering regimes from germination, and the second from emergence of the first true leaf (Plate 3.4). The objective was to reproduce positive and negative ‘crop marks’ and observe the development of the barley plants in response to varying levels of moisture stress relative to an optimal watering regime.

On 10 May 2000, 54 pots were filled with a 1:1 mixture of John Innes No 1 loam-based and Levington M3 peat-based composts. Around 25 seeds were sown onto the surface of each pot and the seeds were watered in lightly. The pots were numbered and a treatment allocated randomly to each number, thus allowing the treatments to be randomised on the glasshouse bench as described for Experiment 2. Treatments consisted of watering optimally, droughting and waterlogging (see Experiment 3 for details). Additionally these watering regimes were introduced to different pots within the individual treatments either from sowing, from germination or from expansion of the first true leaf (Table 3.4). This allowed the factors that can produce germination marks and vegetation marks produced by tillering density in young crops to be investigated, as well as the more traditional ‘crop mark’. It has been suggested (M Brown pers comm) that changes in ground conditions during the growing season, such as a dry spring followed by wetter summer and vice versa, can have an effect on crop mark appearance.



Plate 3.4:

Experiment 4 underway in the glasshouse.

To investigate this suggestion some treatments were changed during the growth period, for example from being droughted to an optimal watering regime, to determine whether this affected growth habit. Finally, the plants were harvested at three separate dates to allow a ‘snap shot’ of the way that growth was proceeding at certain stages. First harvest was completed on 5 June 2000, 26 days after sowing, when tillering had commenced. The second batch of plants was harvested on 16 June 2000 in response to the initiation of flower development. The growth phase of this experiment ended on 19 July 2000 when the plants had reached senescence and the seed heads ripened. The change in treatments was effected from the date that the first batch of plants was harvested. Table 3.4 gives details of the treatments and indicates which plants were harvested first (and hence were not subject to a change of treatment).

Table 3.4: Treatment Regimes for Experiment 4

Pot No	Treatment	Changed To	Applied From
1	Optimum	No Change	First leaf
2	Waterlogged	Optimum	Sowing
3	Droughted	Optimum	Germination
4	Droughted	Harvested	Sowing
5	Waterlogged	No Change	Germination
6	Optimum	Waterlogged	Germination
7	Optimum	No Change	Sowing
8	Optimum	Waterlogged	Sowing
9	Optimum	No Change	Sowing
10	Waterlogged	Droughted	First leaf
11	Droughted	Harvested	Germination
12	Droughted	No Change	First leaf
13	Optimum	Droughted	Germination
14	Waterlogged	Harvested	Germination
15	Droughted	Waterlogged	Sowing
16	Optimum	No Change	First leaf
17	Droughted	Harvested	Sowing
18	Optimum	No Change	Germination
19	Waterlogged	Harvested	First leaf
20	Optimum	Harvested	Germination
21	Optimum	Droughted	Sowing
22	Optimum	Harvested	Sowing
23	Waterlogged	Harvested	First leaf
24	Droughted	Waterlogged	First leaf
25	Waterlogged	Droughted	Germination
26	Waterlogged	No Change	Sowing
27	Optimum	No Change	Germination
28	Optimum	Harvested	Sowing
29	Optimum	Droughted	First leaf
30	Droughted	Optimum	Sowing
31	Waterlogged	Optimum	Germination
32	Droughted	Waterlogged	Germination
33	Waterlogged	No Change	First leaf
34	Droughted	Harvested	First leaf
35	Waterlogged	Harvested	Sowing
36	Waterlogged	Harvested	Germination
37	Optimum	Harvested	First leaf
38	Optimum	Waterlogged	First leaf
39	Droughted	No Change	First leaf
40	Waterlogged	Optimum	Sowing
41	Waterlogged	Optimum	First leaf
42	Droughted	Waterlogged	Sowing
43	Droughted	No Change	Germination
44	Optimum	Harvested	Germination
45	Waterlogged	Droughted	Germination
46	Waterlogged	No Change	First leaf
47	Droughted	No Change	Germination
48	Droughted	Optimum	First leaf
49	Waterlogged	Droughted	Sowing
50	Droughted	Harvested	Germination
51	Waterlogged	Harvested	Sowing
52	Droughted	No Change	Sowing
53	Optimum	Harvested	First leaf
54	Droughted	Harvested	First leaf

Experiment 5: Effects of Soil Depth Variations and Water Availability on the Growth and Development of Compost-grown Spring Barley

This final experiment examined the effects on growth of varying depths of soil. In this group, plants were grown in three different depths of compost to emulate field variations in topsoil depth. In addition, the plants in this growth experiment were subject to the same watering regimes applied in Experiments 3 and 4. This allowed the effects upon growth of variations in soil depth to be examined with and without soil moisture variations. Again, the plants in this group were grown in composts to remove effects caused by nutrient, textural and structural differences.

The literature indicates that variations in soil depth between 30 cm and 60 cm or more have effects on the appearance of barley crops (Jones and Evans 1975, 3; Jones 1978, 657, see Chapter 2). In the light of this information, and having regard for the limitations imposed on the glasshouse experiments by available container size, soil depths of 20 cm, 40 cm and 60 cm were used. Limitations were imposed by space constraints, were further exacerbated by the need to use large containers. Experimental design was limited to one container per treatment, with a large number of seeds sown per container in an attempt to introduce some element of reproducibility to the work. Replication of results was confined to the higher number of plants per container, which is not as reliable as repetition of treatments in separate containers. Given the space limitations this was the best solution to the problem of natural variations in growth affecting results.

Black plastic dustbins were used as containers and the glasshouse space allocated allowed nine bins to be used. Three bins were set up for each soil depth, and each of these was subject to one of the three watering regimes per different soil depth (Table 3.5). The various soil depths were achieved by filling the base of each bin with the relevant volume of washed horticultural gravel. Given the high proportions of riverine deposits in Upper Clydesdale, and the location of many of the crop mark sites upon these lower valley deposits, this was seen as the most appropriate material to use as an experimental 'subsoil'. On 11 May 2000 200 seeds were sown in each bin and, after germination, these were thinned to 100 seedlings. Because of their size and weight when filled it was not possible to move the containers in the glasshouse to reduce the probability of localised environmental conditions affecting growth in the individual containers.

By 13 May germination had begun in each of the containers with plumules visible in all of the pots. On 17 May, the day the watering regimes commenced, the numbers of seeds germinated in each pot were recorded (see Chapter 6). The barley plants were grown on until they reached maturity. Prior to harvesting sections were cut out of each bin to allow the degree of root penetration into the gravel layer to be visually assessed (Plate 3.5).

Table 3.5: Soil Depth and Watering Regime Applied in Experiment 5

Pot No	Depth of Compost	Watering Regime
1	60 cm	Optimum
2	20 cm	Wet
3	20 cm	Dry
4	40 cm	Optimum
5	40 cm	Wet
6	60 cm	Wet
7	20 cm	Optimum
8	60 cm	Dry
9	40 cm	Dry

Because of the small number of treatments involved in this experiment, time and financial constraints allowed for a sample of plant material from each treatment to be analysed using ICP-MS, which is described in the next section. This was particularly valuable as the results of the elemental analyses from the different depth and watering regimes can be used as a comparator for the plants grown in the archaeological soils. If similar patterns of nutrient levels are present in the plants from this experiment and those involving archaeological soils, this will present good evidence for soil moisture differences being a major contributor to crop mark formation. If, however, the patterns are significantly different, the results would then suggest that there are other factors involved in the appearance of the crop marks. This will be discussed extensively in Chapter 6, when all of the threads involved in this study are drawn together.



Plate 3.5a



Plate 3.5b



Plate 3.5c

Plate 3.5:
Experiment 5 underway in the glasshouse.
a) General view of the experimental set-up;
b) Pot no D7;
c) Root penetration, Pot no D7
showing section of the bin cut away to show extent of gravel and root penetration.

Laboratory Analysis of Archaeological Soils and Plant Material

The soil samples separated out from the field samples before the growth experiments commenced were analysed for major and minor elements using ICP-MS. Samples of the harvested dried barley plants were also analysed so that their nutrient status could be determined. The preparation and analysis of the samples was undertaken at Institute of Arable Crops Research (IACR), Rothamstead, Harpenden.

Additional information about the soils and plant material comes from the measurement of the soil pH and conductivity, measured prior to the growth experiments, and the plant and soil magnetic susceptibilities (MS) after the experimental work. The latter technique allows a differentiation to be made between magnetic enhancement of soils due to naturally occurring geological and pedological processes and that due to anthropogenic activity. As with the plant growth work, all data is presented in Chapter 6.

pH and Conductivity Measurements

Samples were taken from each of the soils prior to setting up the Experiment 2 pots. These samples were immediately made into solutions using distilled water, after which the soil pH and conductivity were measured using portable field instruments supplied by IBLS. The same sample was used for each measurement and was prepared by shaking 50 ml of sample with 250 ml of deionised water. Following this first the pH electrode and then the conductivity were immersed in the supernatant solution (White 1987, 108). The resulting pH measurement is that of the bulk solution, and tends to be higher than that of the undisturbed soil, a problem that must be constantly recalled throughout these experiments, for by removing the soils from the site, or in any way interfering with a natural system, that system is changed. However, this is the nature of scientific experimentation, and is an acceptable part of the investigative process. For this purpose the alteration of the pH is not too problematic as all of the samples were treated in a systematic way, and relative differences in measurements should be assured for this reason. As the remotely sensed data upon which this thesis is based is also of a relative nature, this should not be a problem. The measurements are presented in Chapter 6.

Acid Digestion of Samples for ICP-MS Analysis

Aqua regia acid digestion of the soil and plant samples was carried out before ICP analysis. This method is used to determine major and trace element concentrations in the samples, allowing any relative excesses or deficiencies in the soils, the plants, or both to be identified. Any such differences, particularly in the soil compositions, could then be related to geophysical and crop growth responses in the field (Chapter 6). Analysis of the plant material provides a more sensitive indicator of nutrient status than levels detected in soils, and so this data is likely to be more helpful in the assessment of the role of nutrients on crop mark development.

Both sets of samples were ground using a planetary ball mill with agate containers and grinding balls. The finely ground samples were then digested in acid and filtered before being analysed for a suite of nutrient elements. When the samples had been ground to pass through a 2 mm sieve, 0.250 g of each air-dried sample were weighed out and transferred into a 25 ml graduated digestion tube. Samples were processed in batches of 49, which included a repeat of every tenth sample, and the final sample was also replicated. This methodology avoids the need to duplicate all samples and is based on the quality assurance (QA) procedures used at Rothamstead (based on lengthy experience of the technique). One blank sample containing only acid was included in each block; in addition, two standard soil or grass (for soil and plant analyses respectively) samples were included per batch for QA purposes. Once the batches are made up the acid digestion procedure is followed.

Acid Digestion of the Soil Samples

In a fume cupboard, 4 ml of hydrochloric acid (HCl AR, s.g. 1.18) is added to each 0.250g sample, which is then shaken using a vortex tube mixer (whirlimixer). Next, 1 ml of nitric acid (HNO₃ AR s.g. 1.42) is added and this is mixed again (ie 5 ml aqua regia). The mixture is then left to stand for a minimum of 2 hours, but ideally the acids are added to the samples first thing in the morning and left to stand all day, after which they are each mixed again using the whirlimix. The tubes were then put into a Eurotherm silver heating block and heated as indicated in Table 3.6 below. This was timed to be left overnight for ease of working. The acid must be heated up slowly to prevent it from bubbling out of the tops of the tubes. This digestion stage of the procedure leaves a dry residue from which all of the acid has evaporated. 5 ml of 25% HCl is added to each of the residues, the mixture is whirlmixed and the tubes returned to the digestion block for 1 hour at 80°C. After an hour

has passed each tube is whirlmixed again, and approximately 18 ml of deionised water is added to each tube, which are then returned to the digestion block for half an hour at 80°C. After this time the tubes are removed from the block and left to cool in racks at room temperature.

Table 3.6: Heating Regimes for Acid Digestion of Soils and Plants

Ramp No	Temp Rise °C/min	Dwell Time, Min	Dwell Temp °C
<i>Soils</i>			
1	2	120	25
2	2	180	60
3	2	60	105
4	2	120	125
<i>Plants</i>			
1	1	180	60
2	2	60	100
3	3	60	120
4	4	150	200

From IACR in-house methods manual

When the samples have cooled to room temperature, their volume is made up to 25 ml with deionised water. The tubes are capped and shaken to re-suspend the soil residue, and the solution immediately poured out of the tube through filter paper. The first 5 ml of the solution is discarded, with the remaining 20 ml, poured through the same filter paper, and poured into capped Sterilin vials ready for ICP analysis. At least one in every ten samples is duplicated in every batch for QA purposes.

Acid Digestion of the Plant Material

The plant material was digested using a Nitric/Perchloric acid method. This is used for dissolution of plant material by wet digestion for the analysis of major and trace nutrient elements, and is the preferred method where iron analysis is required as HNO₃ alone gives low recoveries of iron. During the digestion the organic matter of the plant is destroyed, the acids removed by volatilisation and the residue dissolved in hydrochloric acid. The methods used to digest the barley plant samples were similar to that used for the soils. The technique differed in the following ways:

Following grinding to pass a 0.5 mm mesh sieve in the agate ball mill, the samples, which had been oven dried following harvest in Glasgow, were once again oven dried at 80°C overnight (minimum drying time is 4 hours) and cooled in a dessicator. Again 0.250 g of each sample was measured into a graduated digestion tube (Appendix 3.1 lists the sample numbers and origin of the soil sample in which they were grown). A 5 ml mixture of nitric/perchloric acid ($\text{HNO}_3/\text{HClO}_4$) was added (15 volumes of 60% HClO_4 AR to 85 volumes of HNO_3 AR (s.g. 1.42)) to each sample and immediately whirlimixed before leaving to stand at room temperature for at least two hours. The samples were then added to the heating blocks used for the soil digestions and heated according to the programme shown in Table 3.6. Again, this was scheduled to run overnight, after which the samples were again allowed to cool at room temperature. At this stage, to prevent residual perchloric from interfering with ICP analysis, the tubes should be almost dry. Once cooled, 5 ml of 25% HCl is added to each tube and the samples were whirlimixed and reheated to 80°C for 1 hour. Next, after whirlimixing again, approximately 20 ml of deionised water is added and the samples reheated for a further half an hour at 80°C, after which the tubes are removed from the heating block and allowed to cool at room temperature. When cool the samples are again made up to a volume of 25 ml with deionised water. Unlike the soil samples, the plant digests are not filtered as the acid digestion completely destroys all of the plant material. They are simply stoppered and mixed well by shaking, making sure to fully invert the tubes. They are then capped and left to settle for a minimum of three hours when they are ready for ICP analysis. Instead of a standard soil sample, a standard stock sample of grass is used for QA purposes during the analysis of the barley plant samples, and again around one in every ten of the samples per batch is duplicated.

ICP-MS Analysis of Archaeological Soils and Barley Plants from the Case Studies

Following acid digestion, the plant and soil samples were analysed to determine their elemental concentrations using ICP-MS. Details of the technique and theory behind it are well-documented in the literature (Jarvis *et al* 1992; Garrison 2003, 222-30). This established technique in the soil and plant sciences allows suites of numerous elements to be measured at one time. It is also widely used in archaeological science to analyse archaeological ceramics and lithics for information on origin (Pollard and Heron 1996, 33f; Henderson 2000, 312), and is instrumental in the search for indicator elements at historic farming settlements by researchers at Stirling University (Wilson *et al*, in prep)

As this is a specialised analytical technique this part of the analysis was undertaken by Mr Adrian Crosland of IACR, who also supervised the preparatory work outlined above. All of the samples were analysed for the suite of elements listed in Table 3.7, and the original output from the analysis is shown in Appendix 3.2.

This is the suite of elements that samples are routinely analysed for at IACR. The soil and plant samples analysed were from Experiments 2, 3, 4 and 5. The results of the analyses from all of the experimental groups are presented and discussed in Chapter 6.

Table 3.7: Elements Measured During ICP-MS Analysis of the Plant Material and Soils from the Case Studies

<i>Element</i>	<i>Chemical Symbol</i>
Aluminium	Al
Calcium	Ca
Cadmium	Cd
Cobalt	Co
Chromium	Cr
Copper	Cu
Iron	Fe
Potassium	K
Magnesium	Mg
Manganese	Mn
Molybdenum	Mo
Sodium	Na
Nickel	Ni
Phosphorus	P
Lead	Pb
Sulphur	S
Titanium	Ti
Zinc	Zn

Leaf Area Index Measurements

A quantitative means of measuring differences in individual plant growth density is the leaf area index (LAI) of the plant. The LAI is the area of the leaf surface in m² divided by the ground area that the plant represents. This gives a numerical value to the qualitative descriptions of growth habit given in preceding parts of this chapter. However, because the plants measured came from a glasshouse experiment, the indices for each were not calculated. Instead, in Chapter 6, the absolute areas of the plants per pot have been compared. At IACR use was made of the Leaf Area Machine from Delta-T Devices,

Burwell, Suffolk, a device that calculates the area of leaf per plant using a light source and photocell.

Following harvest of Experiment 2 plants grown in the soil samples from Burnfoot Farm (Case Study 2) the plants were photocopied using a standard office photocopier and the copied silhouettes were carefully cut out from the paper. These 'copies' of the plants were fed into the leaf area machine, which has a rolling platform designed to flatten out the paper 'plants' and measure them as they move across the illuminated area below the photocell. The machine, used in continuous-add mode, was first calibrated with 100 cm² of graph paper, coloured black and cut into irregular leaf shapes. For ease of measurement the instrument was calibrated for a 200 cm² of graph paper and the figure for each plant was then divided by 2 to ensure it was relative to the actual area of the calibration graph paper (100 cm²). The area of the plants measured was then calculated relative to this calibrated figure. The calibration number changes during the measuring run due to instrument drift. Because of this the machine was re-calibrated at regular intervals throughout the measurement period and zeroed after measurement of each plant. The LAI is calculated from the manually recorded readings, using the relevant calibration number for each individual run, and the following calculation:

$$\text{Reading from LAI instrument} \times 200 / \text{calibration number}$$

Magnetic Susceptibility Measurements

Bench MS measurements were made on plants grown in, and soils sampled from Case Study 1 using the MS2B laboratory coil made by Bartington. A small number of plant samples from Experiment 4 that had been analysed using ICP-MS were also included in the MS measurements. Measurement of plant and soil samples, although carried out separately, employed the same methodology.

The samples were placed into 10 ml cylindrical bottles, supplied along with the instrument, which were then lowered into the sensor individually for measurement. Care must be taken to ensure that the sample is placed centrally on the platen of the instrument as position can affect measurement of the sample. Each sample was weighed prior to measurement, which allowed mass-specific susceptibility measurements to be made, using the SI system (Units:

$10^{-8} \text{ m}^3 \text{ kg}^{-1}$, rather than cgs, the alternative measurement setting on the instrument). The computer program Multisus, also supplied by Bartington, is the interface through which the instrument is run, and the program prompts the user to perform the measurement steps, and corrects for the weight and MS of the container before automatically recording the mass-specific MS for each sample in an Excel-compatible spreadsheet.

The instrument was first left to equilibrate for around an hour, and was then checked for around 10 minutes to ensure it was stable, by logging air readings (measurements with no sample inserted) with the instrument zeroed. A constant zero indicated that the instrument was ready for sample measurement. First the container plus sample weight was entered then an air reading was taken. For each sample, the air measurement was logged followed by insertion and measurement of the sample, followed by a further air reading. This procedure was repeated ten times per sample, and the readings were then automatically averaged and saved. This procedure was carried out first at Low Frequency for each sample, and then the measurement routine was repeated with the instrument set at High frequency. As each high frequency averaged reading was added to the spread sheet, the program automatically calculated the frequency dependency MS of the sample.

Fine-grained materials, such as soils, exhibit frequency dependent (FD) MS, which becomes more significant for single-domain grain sizes (c. $0.03 \mu\text{m}$ diameter). Generally, these grain sizes are widely distributed throughout the medium, which causes a fairly uniform FD response in the low kHz range, in which the MS2B instrument operates. Frequency dependent MS (χ_{FD}) figures with negative signs indicate that the material has a diamagnetic component, and in combination with the actual figures, these measurements provide an insight into the form and origin of the magnetic materials in each sample. This is discussed further in Chapter 6.

In the MS2B sensor the ratio of low frequency to high frequency (LF:HF) is 1:10, that is the LF measurement is made at 0.465 kHz, and the HF at 4.62 kHz. So χ_{FD} is defined as the change in MS when the frequency is increased by 10 kHz. χ_{FD} is the coefficient of frequency dependency, which is calculated using the formula:

$$\chi_{\text{FD}} = \frac{\text{change in MS}}{10f/\chi_{\text{LF}}}$$

where:

f = frequency

χ_{LF} = Low Frequency MS. This always has the higher value of the two measurements.

The percentage FD is calculated by:

$$\chi_{FD} \% = 100\{(\chi_{LF} - \chi_{HF})/\chi_{LF}\}$$

where:

χ_{LF} = Low Frequency; χ_{HF} = High Frequency

The results of measurements made on soils and plants from Case Study 2 are presented in Chapter 6.

3.5 Summary and Discussion of the Experimental Work

Table 3.8 summarises the experimental work carried out during the course of this research. The results of the work described in this chapter are presented in Chapter 6. This work allows a comparison of results gathered aerially and on the ground geophysically. The relationships between these responses are examined for each of the three Case Studies in Chapter 5. The experimental soil and plant work allows us to test whether there is enhancement or depletion of certain nutrient elements in the plant material due to an increased or decreased availability of water alone, a factor known to influence crop mark formation. In Chapter 6 this is examined by comparing the values of elements taken up by the crop plants with both normal and differential growth, and determining similar relative proportions of these elemental differences in the soil. This in turn should allow judgements to be made about the mobility and uptake of elements within the crop and above the archaeological features. Comparison with the results from archaeological soils will allow an assessment of whether archaeological crop marks are a result of cultural and pedological differences, or whether they are a function of increased elemental reserves due to anthropogenic activity. Additionally the results will allow an assessment of whether the total concentrations of all elements change between archaeological features and soil

‘background’, shedding light on the likelihood of an electromagnetic source of at least some of the anomalous areas. The findings from all strands of the investigation will be brought together in Chapter 7.

Table 3.8: Summary of the Experimental Work Outlined in Chapter 3

<i>Type of Work</i>	<i>Non-site Specific Investigation</i>	<i>Case Study 1</i>	<i>Case Study 2</i>	<i>Case Study 3</i>
Aerial reconnaissance	No	Yes	Yes	Yes
Transcription of aerial photographs	No	Yes	Yes	Yes
Magnetic survey	No	Yes	Yes	Yes
Resistivity survey	No	Yes	Yes	Yes
Soil samples taken from excavated contexts	No	Yes	No	Yes
Soil samples taken from Auger survey	No	Yes	Yes	No
Experiment 1	Yes	No	No	No
Experiment 2	No	No	Yes	No
Experiment 3	No	Yes	No	No
Experiment 4	Yes	No	No	No
Experiment 5	Yes	No	No	No
pH measurements of soil samples	No	Yes	No	No
Conductivity measurements of soil samples	No	Yes	No	No
ICP-MS analysis of soil samples	No	Yes	Yes	Yes
ICP-MS analysis of plant samples	Yes	Yes	Yes	No
LAI measurements	No	No	Yes	No
Magnetic Susceptibility measurements	Yes	Yes	No	No

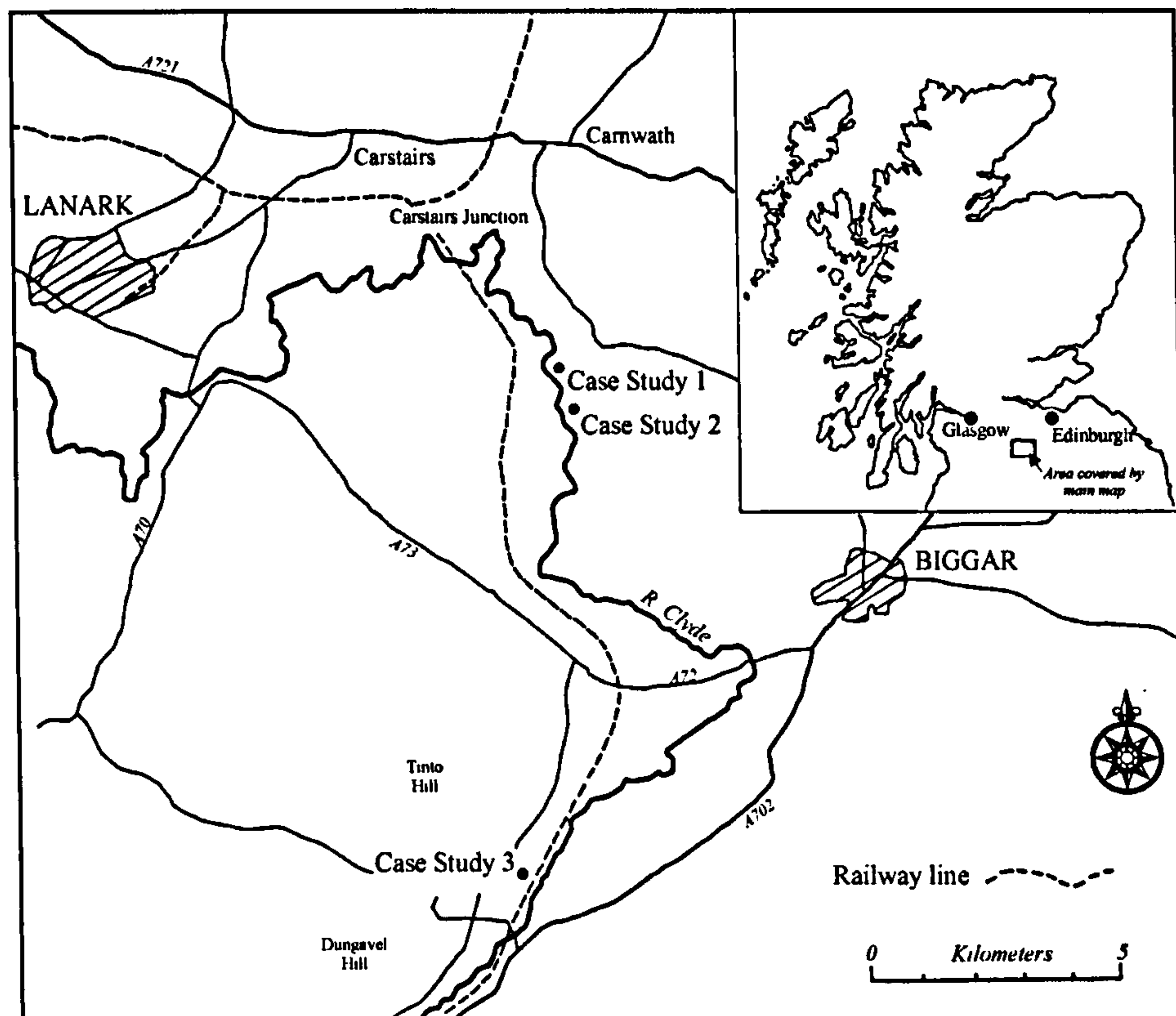
Chapter 4: The Upper Clyde Valley: The Case Studies in Context

4.1 Introduction

Three sites located in the Upper Clyde Valley, Lanarkshire, in southern Scotland have been chosen as case studies to test the hypotheses outlined in the preceding chapters. The opportunity to use these sites arose from my involvement in a research project at Glasgow University Archaeology Department (GUAD). This chapter gives a brief overview of the project, its aims, and the way in which this research is associated with that of the project work. A final publication that explores the development of the archaeological landscape and presents the information derived from the 27 individual case studies undertaken during the course of the project is in preparation (Hanson and Sharpe in prep).

The starting point and original stimulus for the Upper Clyde Valley Landscape project (UCVLP) was the availability of aerial photographic information for the area. Whilst flying in the area to record cropmark sites as part of a wider programme of regional reconnaissance in the western Lowlands, funded by the Royal Commission on the Ancient and Historic Monuments of Scotland (RCAHMS) and GUAD, Prof. Bill Hanson had noted the particular richness and diversity of the archaeological remains. The study area represents one of the densest distributions of archaeological sites in the western lowlands. The good quality arable land here affords an extensive aerial record of the archaeology. This, together with the existence of a range of artefacts recovered as stray finds, made this area an obvious choice when seeking to put into practice the call for greater integration of different survey techniques, particularly aerial reconnaissance, geophysical survey and arable fieldwalking, in order to promote the examination of archaeological landscapes on a regional scale (Hanson and Macinnes 1991). Accordingly, a detailed proposal was put to Historic Scotland (HS) to help fund a 5-year partnership project with GUAD. This application met with approval and the UCVLP commenced in May 1996, to which I was appointed research assistant. The aims of this project were to investigate the archaeology of an area of the Upper Clyde river valley to gather information about, and gain a deeper insight into, the historic and prehistoric evolution of the area. The work for both the UCVLP and this thesis frequently coincided in the early stages as the basic framework for the development of the

area was established by a combination of desk- and field-based work. Later, the project work, and familiarity with the area that it brought, helped to inform the choice of sites for this thesis. Thereafter the two pieces of work diverged.



*Figure 4.1:
The location of the UCVLP study area and Case studies.*

The study area of the UCVLP encompasses a roughly square area with Lanark lying just outside to the north-west, and Biggar and Coulter in the south-east (Figure 4.1). In terms of maps, the area encompasses Ordnance Survey (OS) Map sheets NS93, NS94, most of NT04 and some of NT03. The area is defined by the limits of the River Clyde watershed. This coincides almost exactly with the county boundary between Peebles-shire and Lanarkshire in the east, where the boundary line runs approximately along the Southern Uplands Fault (SUF). This marks a change in topography from low-lying river valley to high, rugged uplands. The valleys of the Mouse Water, the Medwin and South Medwin rivers, and their tributaries mark the watershed in the north. In the south the area is defined by the smaller streams draining into the Clyde, and is constrained by the extent of the southernmost OS map sheets, providing a geographically manageable study area. The area contains a

remarkable number and array of archaeological sites, numbering over 800, including find spots of artefacts (Hanson and Sharpe in prep), and the archaeological remains indicate an area settled from early prehistory onwards.

4.2 Nature of the Archaeological Evidence

The archaeology of the area is preserved in a number of ways. There are a significant number of extant sites, including buildings dating from the 15th and 16th centuries. There are 21 known hill forts and many cairns and field systems have been recorded, for example on Horse Law. Some of the sites, on the other hand, survive only as historical records, while others exist as scatters of lithics and pottery across ploughed fields, or as crop marks.

This range of surviving remains illustrates the need for a diverse approach to their study. The area was investigated utilising historical and archaeological records of previous discoveries, modern and historical maps, collections of aerial photographs and artefacts, and through visits to the sites. Arable fieldwalking was undertaken to look for artefactual evidence of past activity and geophysical survey employed to augment and clarify the data from selected sites. In the final stages of the project, limited excavation at a number of carefully chosen sites proceeded in an attempt to retrieve evidence of the date and function of a representative selection. It was at this stage that two of the three Case Studies were excavated, and for the purpose of this thesis the aim was to provide soil samples from secure contexts and to investigate the physical causes of the crop and geophysical responses to the remains.

One important aspect of the multi-assessment approach was the use of GIS which allowed information from the project database, aerial photographic transcriptions, topographic, soil and geological maps to be combined. The aim was to facilitate an overview of site distribution, the identification of relationships between sites and, for example, their topographic or pedological settings, and highlight areas that apparently contain no archaeological remains. GIS also assisted in the decision to use the three sites for this study, allowing a combination of different geologies, soils and topographies to be selected for the morphologically similar site types. The three sites are introduced in detail below.

4.3 The Landscape of the Study Area, and Its Evolution

There follows an introduction to the landscape setting of the UCVLP study area and the agencies that were, and in most cases still are, responsible for its evolution. Starting with the geology, then moving on to the soils and topography of the area, the remainder of this chapter lays down the background against which the three Case Studies are set.

Solid Geology

Immediately apparent on a geological map of Scotland (Figure 4.2) is the north-east - south-west regional trend of the geological units, faults and igneous dykes of Tertiary age (up to 65 Ma). This trend is due in part to the closure of Iapetus, the ocean that separated the two tectonic plates on which Scotland and England then lay, and the stresses and strains imposed on the rocks during that process. In the Clyde Valley (Figure 4.3), the trend is most apparent in the faults that run in this direction, not least the Southern Uplands Fault (SUF), which runs from the West coast of Scotland, from above Cairnryan (NGR: NX 0471), across in a North-easterly direction to Dunbar (NGR: NT 6677) on the East coast (Cameron and Stephenson 1985, 129). On the North side of the SUF, which delimits the Southern extent of the Midland Valley, are a number of smaller, associated faults. The most significant of these in the study area is the Carmichael Fault. South of the SUF the Southern Uplands begin, and the solid geology changes from the younger rocks of the Midland Valley to older Ordovician rocks (445 - 510 Ma) (BGS 1979).

In Clydesdale, the consequences of these catastrophic events reveal themselves in the geology of the study area (Figure 4.3). To the north of the faulted area, in the Midland Valley, lie gently deformed rocks of mainly Carboniferous and Devonian sedimentary origins, along with some Carboniferous igneous rocks seen to outcrop to the north of Biggar, for example those centred at NT05 39 and NT07 45 (Cameron and Stephenson 1985, 129). The Midland Valley is thought to have moved downward relative to the land south of the SUF during the Devonian and Carboniferous periods, producing a fault structure known as a graben. This downward movement on the Midland Valley side of the fault is responsible for the rich coal resources that have been exploited in South Lanarkshire. The resulting deep, downthrown basin allowed the accumulation of great depths of younger sediments and organic remains in the shallow warm seas that covered the Midland Valley at this time.

Correspondingly, the youngest strata lie in the north of the study area, on the downthrown, northern side of the SUF. There are Lower Old Red Sandstone (ORS) rocks of Carboniferous to Devonian age; fine-grained greywackes and sandstones; Upper ORS sandstones and occasionally limestones, such as the cornstone outcropping along the bed of the river Clyde between Hyndford and Millhill (NS 925 417), so named because its alkaline nature causes enhanced cereal growth where it is present due to changes in soil pH, a geologically induced cropmark recognised historically by farmers. A broad band of older, predominantly sandstone, Silurian rocks, trending in the regional direction (north-east - south-west), outcrop for around 11 km, comprising and surrounding Chester Hill (NS 953 396), the setting for one of the many hilltop forts in the UCVLP area (Figure 4.3).

Igneous activity during the Devonian and Carboniferous is largely responsible for the remaining hills and high lands, moorland and poorly drained areas where peat has accumulated in the north and north-west of the study area (Plate 4.1). During the Devonian, and contemporaneous with the deposition of the Lower ORS rocks, lava conglomerates and felsite dykes, sills and plugs were being erupted and emplaced in the area. This igneous activity was associated with faulting and movement at the SUF and associated faults during the collision of the continents. The resulting harder igneous rocks survive today as Swaites Hill, Carmichael Hill, Tinto Hill, and are exploited in the quarry at the former Cairngryffe Hill (Plate 4.2). Quarrying of this resource represents a significant threat to the archaeology of the area, particularly for upland defensive and funerary sites.

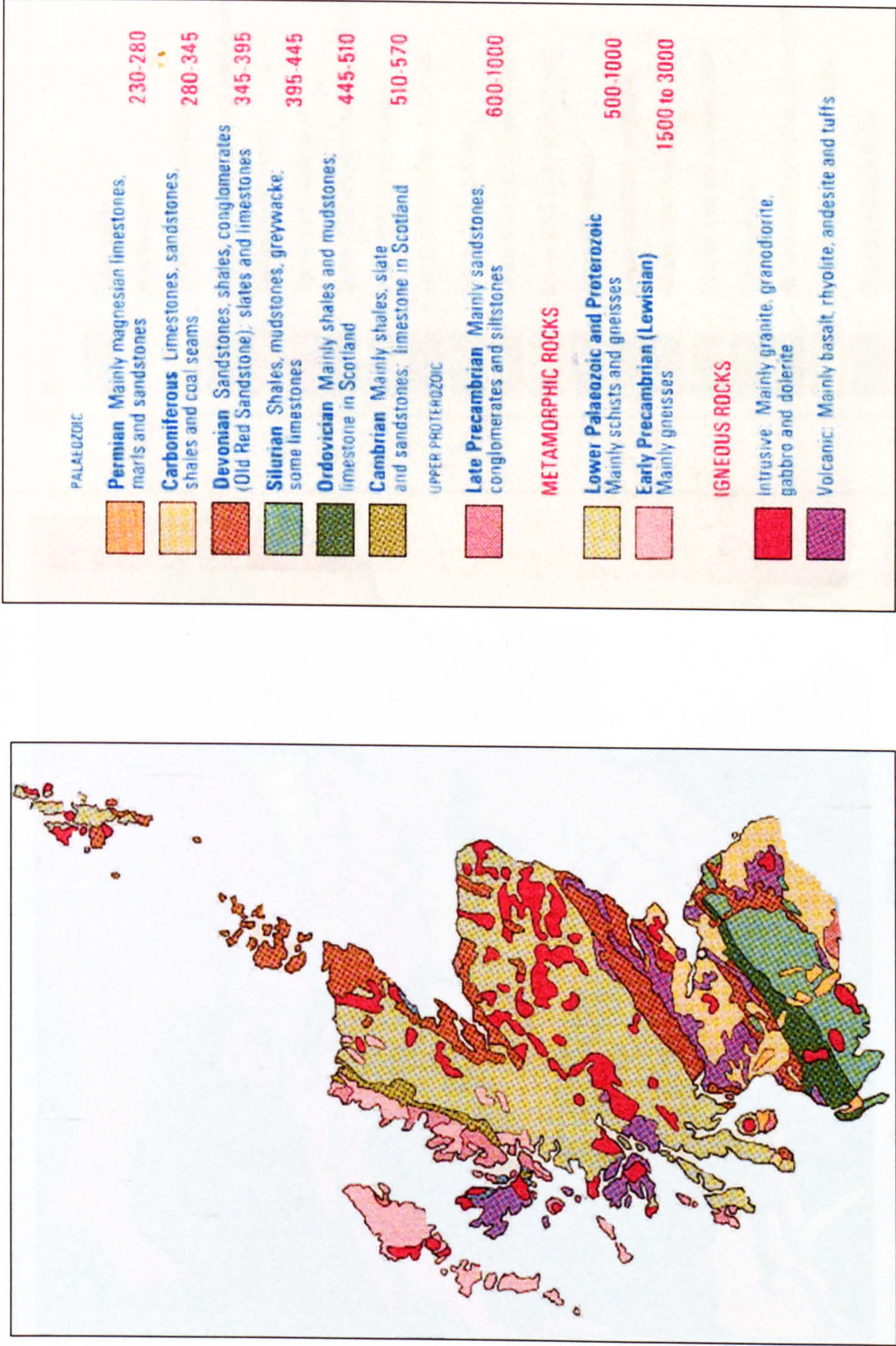


Figure 4.2:

Geological map of Scotland and the stratigraphic column. © BGS.

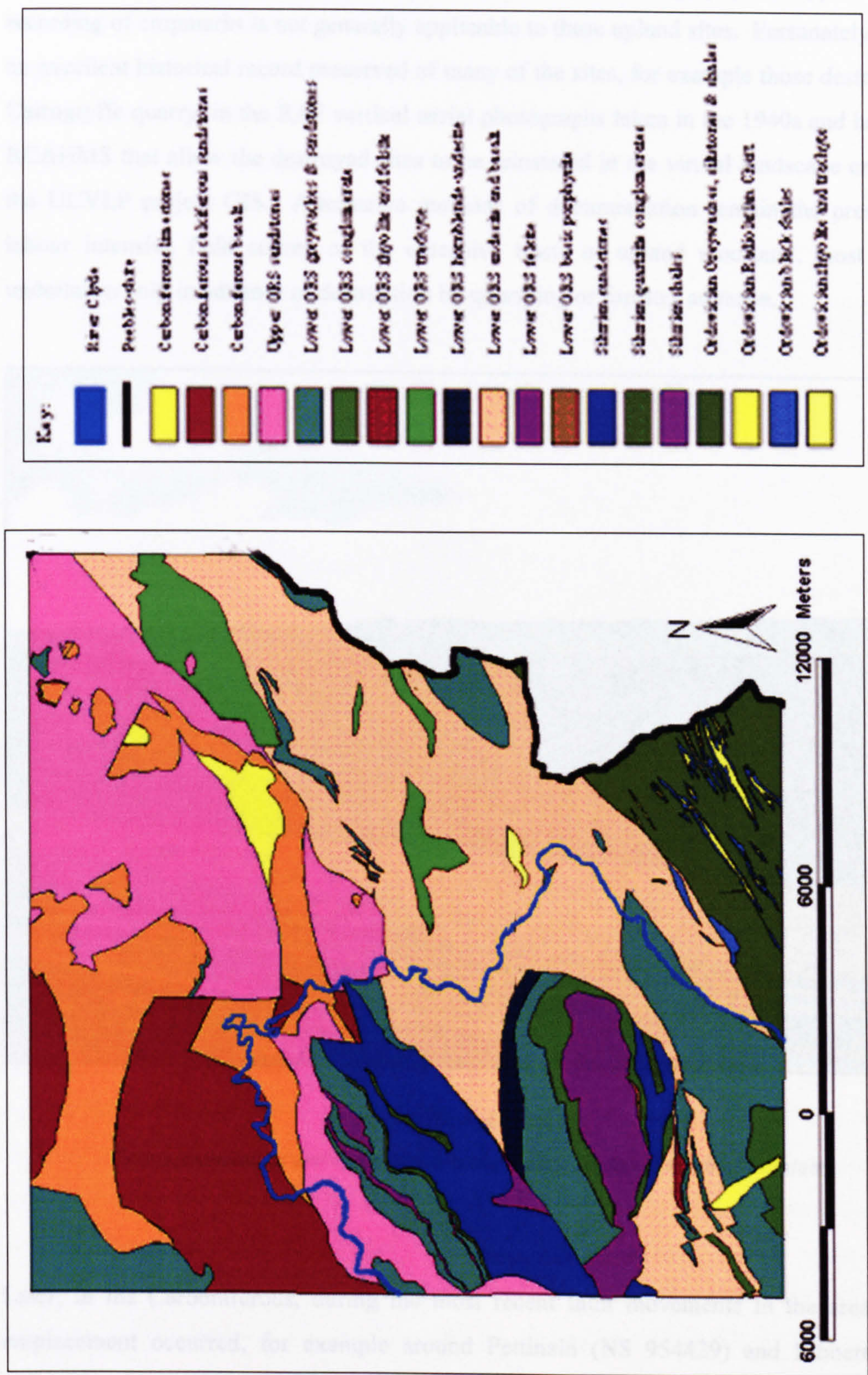


Figure 4.3:
Solid Geology of the UCVLP area. After BGS.

Traditionally these igneous terrains are assumed unsuitable for geophysical investigation, particularly for magnetic survey. Additionally, aerial photography as applied to the recording of cropmarks is not generally applicable to these upland sites. Fortunately there is an excellent historical record preserved of many of the sites, for example those destroyed by Cairngryffe quarry, in the RAF vertical aerial photographs taken in the 1940s and housed at RCAHMS that allow the destroyed sites to be reinstated in the virtual landscape created in the UCVLP project GIS. Alternative methods of documentation remain the preserve of labour intensive field survey of the extensive tracts of upland moorland, most usually undertaken only in advance of destruction by quarrying or forestry advance.



Plate 4.1:

Peat accumulation and exploitation in the study area to the north of Carstairs.

Later, in the Carboniferous, during the most recent fault movements in the area, basalt emplacement occurred, for example around Pettinain (NS 954429) and Libberton (NS 990429), and to the north of Carstairs (around NS 95 48), extending around Couthally Castle (NS 972 483). These basalts may have impeded drainage enough to result, together

with climatic conditions, in the Mosses mapped on the first edition of the OS maps, and which still exist today (White 1987, 145; Godwin 1981; Plate 4.3). The basalts are associated with consolidated marine sediments such as limestones, cementstones, sandstones and carbonaceous shales with thick oil shales where the upper part of this formation, the Carboniferous Limestone Series, is present. Well-developed marine limestones and calcareous shales indicate repeated returns to periods of marine conditions, whilst coal seams present within these marine units indicate periodic emergence of land.



Plate 4.2:

Tinto Hill from the north.

The SUF is accompanied by a broad zone of faulting around 8.5 km wide, with the Carmichael Fault marking the northern extent. The Carmichael Fault runs parallel to the SUF, passing to the north-west of Level Hill (NS 90 34), the western extent of the igneous mass that comprises, amongst others, Tinto Hill (NS 95 34). From here it continues to the west of Thankerton (NS 973 382) before terminating in a roughly north - south trending minor fault (NS 98 40). This minor fault cuts across the bed of the River Clyde as it meanders north-westwards past Burnfoot (NS 97 40) and Townhead (NS 98 42) farms. Two of the three Case Studies lie close to this area (Figure 4.1).

Much of the solid geology associated with this area of faulting comprises igneous rocks. This is common in areas of disturbance where there has been much movement of the Earth's crust. Within the faulted zone there are Devonian Lower ORS-age igneous rocks, including basalts and andesites. These outcrop around Covington (NS 974 396) and Thankerton, on the south side of Tinto and up to Ewe Hill (NS 90 31).



Plate 4.3:

Blacklaw Moss (NS927486) is typical of the north western UCVLP area, where the main modern land usage is peat and drift extraction.

On the south side of the SUF the rocks are much more strongly folded and faulted, again reflecting the chain of events leading to the closure of Iapetus. The complicated succession of rock types and structures found here is thought to result from the 'stacking up' of rock units and sediments that once lay on the ocean floor. These were brought to the continental surface as the Eurasian plate was subducted beneath the North American one when Scotland and England joined (Cameron and Stephenson 1985, 127). As none of the case studies is located on these geologies, the reader is referred to the UCVLP report for details (Hanson and Sharpe in prep).

Drift Geology

Once the landmasses had merged and the volcanic and igneous activity ceased the processes of chemical and mechanical weathering, not least due to glacial action, began to influence the landscape. The drift geology recorded in the study area today can be loosely identified as distinct accumulations of more recent (in geological terms) sediments in response to climatic influences. This is important to this study, as will be seen in Chapter 5, as it exerts an important influence on the results of particularly geophysical survey. Most importantly the effects of glacial activity in the area have shaped the modern landscape by the erosive actions of ice which reworked the topographic features, thought to have been established in the Tertiary period, and by the deposition of eroded materials left in the wake of the massive ice sheets. These deposits are said to be the only stages of the Quaternary (*c* 2Ma-Present) that can be identified in the Midland Valley, because the last glaciation destroyed any evidence there may have been of any earlier depositional events (Greig 1971, 98; Cameron and Stevenson 1985, 4). The drift deposits tend to be thickest in the valleys and thin to absent over the hills and high areas. This helps to explain both the ancient and modern concentration of settlement and farming activities in the low-lying areas, where the weathering of the deposits allowed soils to form.

The last glaciation to affect the study area occurred in the latter part of the Devensian stage (Figure 4.4). The main direction of ice flow was southwards from the western part of the Grampian Highlands. To a lesser extent the ice also spread northwards from the Southern Uplands (BGS 1981). The height of this glaciation is thought to have been around 16,000BC when the ice is estimated to have been up to 1500 – 1800 m thick. Evidence from outwash deposits, glacial striae and drainage channels suggest that at its maximum the Highland Ice-sheet extended to the margins of the Southern Uplands, well to the south-east of Biggar. As this ice sheet retreated, the Southern Uplands ice sheet advanced north, where it had previously been restricted by the Highland ice, reaching the southern flanks of the Pentland Hills, again blanketing the study area (BGS 1981). Shortly after 11,000BC the Midland Valley was ice-free (Cameron & Stevenson 1985, 133). For around 1000 years it appears that the climate was similar to that which we experience today. This period, the Windermere or Late-Glacial Interstadial, ended with the Loch Lomond Re-advance. This stage marked a deterioration in the climate and, between *c* 9000 and 8300BC, the advance of glaciers into the Midland Valley again. Towards the end of the Devensian Stage, at around 8000BC, the rapid improvement of the climate resulting in the end of glaciation marked the

beginning of the Flandrian Stage (BGS 1981). As the climate improved features associated with glacial retreat, principally ablation till, were laid down. The colour and composition of the till varies depending on the source of the rocks from which it was eroded, from the north of Scotland or the Southern Uplands, and on the stage of the glaciation in which it was deposited, that is whether it is lodgement or ablation till. The former is deposited below an ice sheet as it advances, whilst the latter is laid down from the melting ice as it retreats. Undisturbed lodgement till is described by Cameron and Stevenson (1985, 136) as “commonly a very firm, tough deposit”, that tends to be overlain by more sandy, roughly stratified ablation till. Because ablation till is associated with the erosive forces of melting ice, it often contains large angular boulders, a characteristic of glacial material that is not far travelled, and usually of local rock types (BGS 1981). Glacially eroded debris of this nature carried in meltwaters in, below and on the ice sheets was eventually deposited in Clydesdale to produce fluvioglacial features comprising till largely derived from the underlying solid bedrock, but which also included fragments of rocks transported over very large distances. For example, outwash sand and gravels overlie boulder clay with Highland erratics in a central belt between Symington (NS 99 35) and West Linton (NT 14 51), following the line of the modern A702 road. These Highland erratics are also seen in basal boulder clay in the north and west of the area where the topography is generally more subdued over the younger Carboniferous and Devonian rocks, resulting in a reasonably constant drift cover (BGS 1981). In the more undulating topography to the south-east of the UCVLP area this drift is restricted to the valleys, as described above.

Till derived from Devonian, ORS-Age or Permian sources generally has a reddish brown sandy matrix and contains red sandstone blocks and boulders. That derived from Carboniferous sediments tends to comprise a dark brownish-grey, clayey or silty matrix with inclusions of brown and yellow sandstones, grey shales and igneous fragments (Greig 1971, 98). Where the till is derived from Ordovician or Silurian rocks from the Southern Uplands it too tends to consist of a brownish-grey matrix but with lithic fragments mainly of greywackes and hard shales. The differences in the materials making up the drift deposits will affect not only the soil types that can develop, as is discussed below, but will also have an effect on drainage and other properties. This has implications for the suitability of land for different anthropogenic activities and on the ability to detect aerially and geophysically any remnants of this activity.

The Flandrian Stage commenced around 8000BC, marked by an improvement in climate from the harsh, arctic glacial conditions that preceded. Once glacial activity had ceased the land gradually became vegetated, and woodland and forest became established (Cameron and Stevenson 1985, 143). Between 3000 - 1000BC, people are known to have been living in the Clyde valley, and had begun to clear the woodland that became established during the Flandrian (Cameron and Stevenson 1985, 143). During the course of the UCVLP evidence that the area was inhabited much earlier than this, in the Mesolithic, was found along many of the watercourses, most particularly around the Medwin Valley and to the north of Biggar.

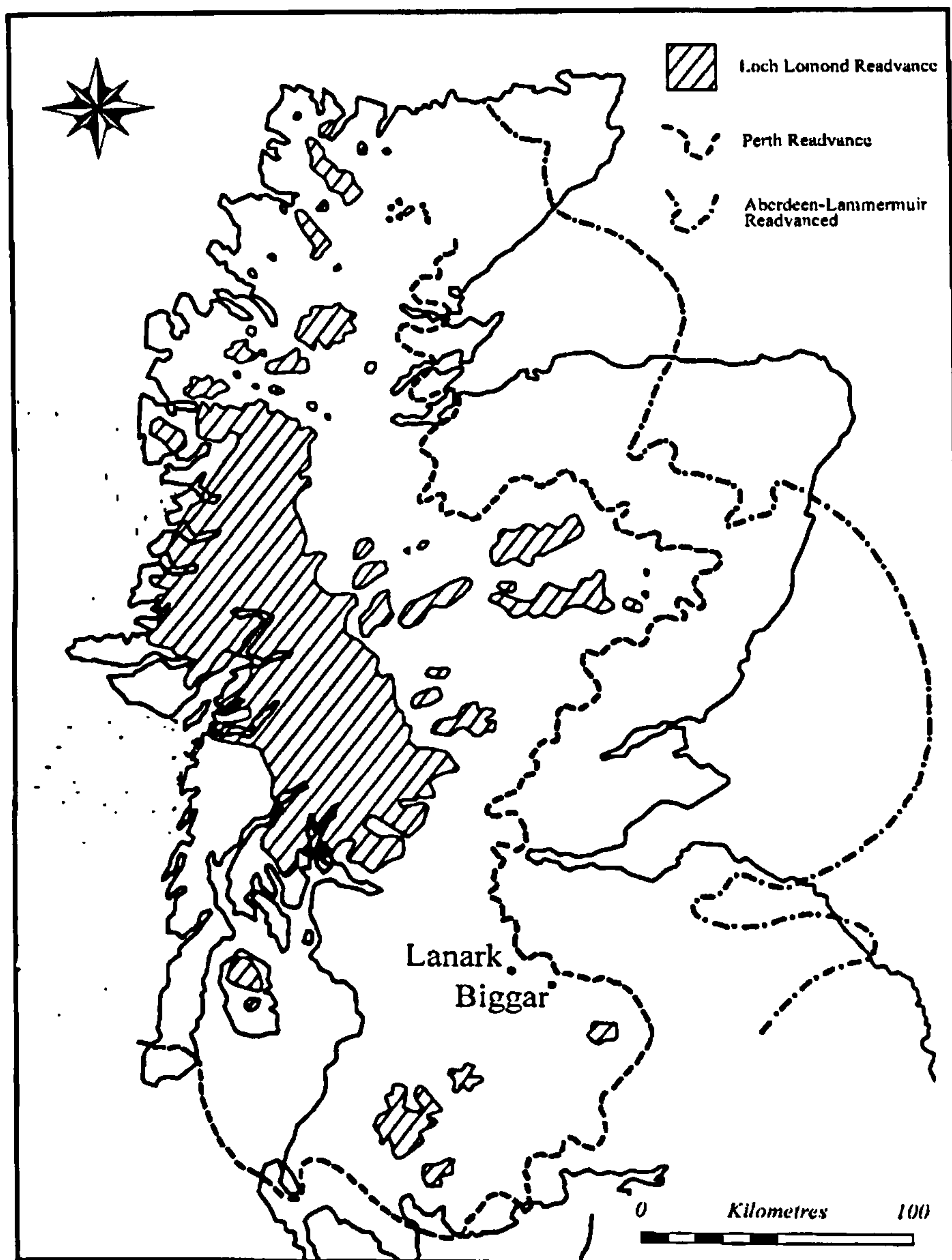
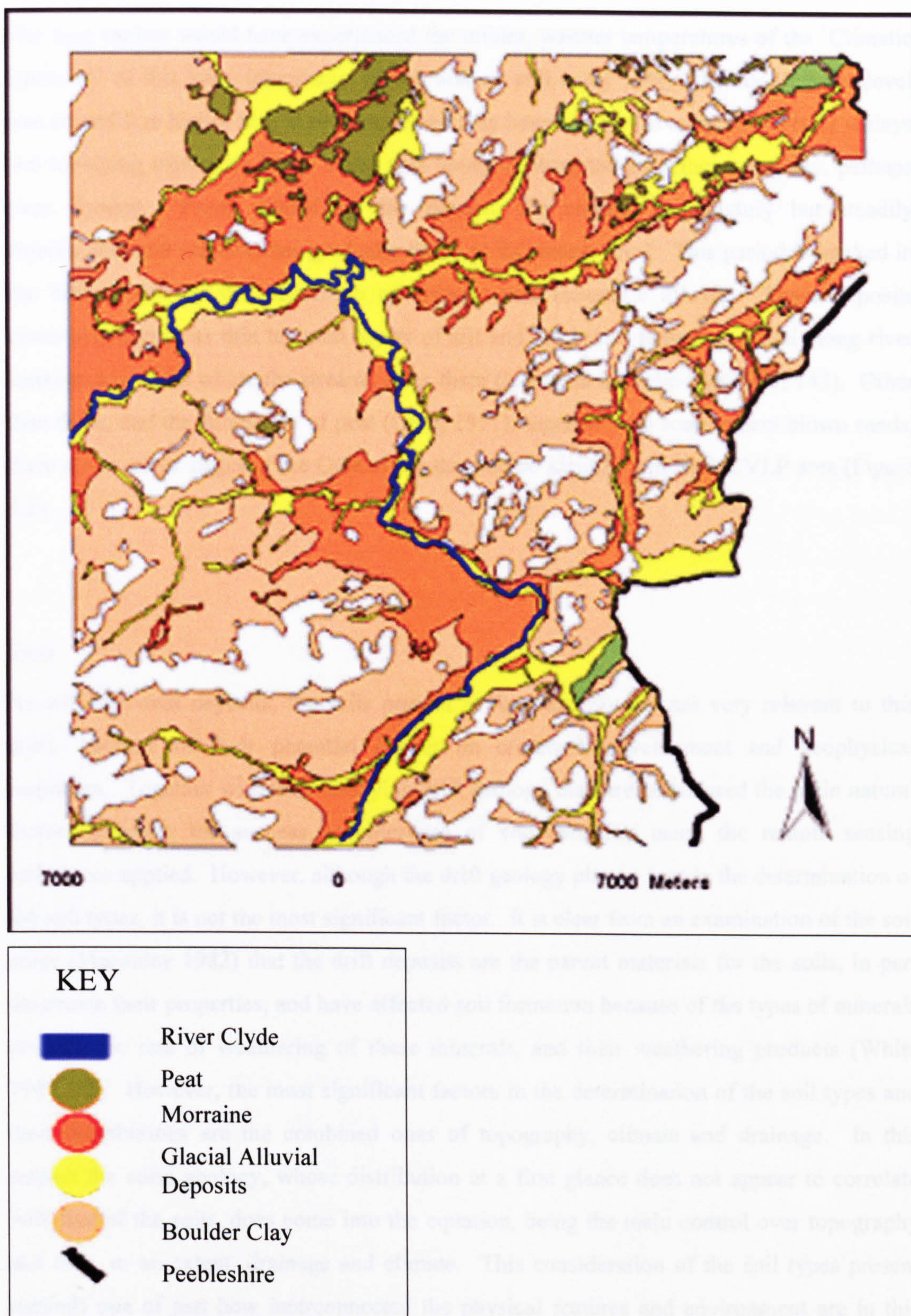


Figure 4.4:
Glaciations affecting the UCVLP area. After Sissons 1967.



*Figure 4.5:
Drift cover in the UCVLP area. After BGS.*

The later settlers would have experienced the milder, warmer temperatures of the 'Climatic Optimum' of this latest interglacial period that we still enjoy today. At this time sea level was around 8 m higher than at present, which may have resulted in many of the river valleys and low-lying tributaries in the study area being much wetter than they are today, perhaps even flooded. From 1000BC to the present, the climate has slightly but steadily deteriorated, and sea level has gradually fallen to its present level. This period is marked in the drift record by the deposition of riverine and lacustrine alluvia. These deposits commonly appear as thin terraced layers of silt and sand with lenses of gravel along river banks and in lochs where the streams enter them (Cameron & Stevenson 1985, 143). Other than these, and the deposition of peat (Greig 1971), together with some recent blown sands, there are no other stages of the Quaternary that can be identified in the UCVLP area (Figure 4.5).

Soils

As with the drift deposits, the soils present at the Case Studies are very relevant to this thesis because of their potential impact on cropmark development and geophysical responses. Together with the underlying drift geology they are considered the main natural factors affecting the success or otherwise of site detection using the remote sensing techniques applied. However, although the drift geology plays a part in the determination of the soil types, it is not the most significant factor. It is clear from an examination of the soil maps (Macaulay 1982) that the drift deposits are the parent materials for the soils, in part determine their properties, and have affected soil formation because of the types of minerals present, the rate of weathering of these minerals, and their weathering products (White 1987, 79). However, the most significant factors in the determination of the soil types and their distributions are the combined ones of topography, climate and drainage. In this respect the solid geology, whose distribution at a first glance does not appear to correlate with that of the soils, does come into the equation, being the main control over topography and thus, to an extent, drainage and climate. This consideration of the soil types present reminds one of just how interconnected the physical features and environment are in this and any other system. It gives a taste of the many factors that must be considered when trying to examine the occurrence of cropmarks and the preservation and discovery of archaeological features. White (1987, 65) describes work by Jenny in 1941, which cites the most important factors in the formation of soil as being its parent material, climate, soil- and

other organisms, relief and time. Initially parent material and relief are the important factors governing soil development, which then give way to the chemical and biological reactions involved. The organisms present and the climate determine the nature and speed with which the reactions take place, leading finally to time becoming the important factor in that it determines the extent to which these factors proceed and develop (White 1987, 65). Climatic factors play a significant part in the soil types that develop. Specifically, the twin components of moisture and temperature are important (White 1987, 71). The effectiveness of moisture to form a soil depends on such factors as the form and intensity of precipitation, evaporation, the slope of the land and the permeability of the parent material.

Both the parent material and the climate have major influences on the pioneer plants that initially colonise the weathering plant material, and these in turn determine the final climax community of vegetation that exist in the area. This is very important as the plant communities profoundly affect the soils that develop (White 1987, 72). The vegetation cover also affects the animal communities that colonise the soils, and this is a very significant part of the soil forming process. For example, earthworms are the most important of the soil forming fauna in temperate regions, but leaf litter which is acidic, such as that from pine, spruce and larch, is unattractive to them. The lack of earthworm activity in this environment results in the accumulation of litter at the soil surface. Under deciduous forest, especially that of elm and ash, the litter is incorporated into the soil by earthworms that ingest it and combine it into the soil as faeces. At the same time, the litter is mixed with ingested mineral particles creating a stone-free surface layer through casting.

Relief is indicated in local climatic, vegetation and drainage conditions, and so affects the soils that develop. Particularly, angles of slope play a significant role in soil type distribution, mainly due to changes in drainage conditions (White 1987, 74). It is possible to identify soils, which may have the same parent material, that change from freely drained oxidised soils at the top of slopes, to poorly drained gley soils at the valley floors. This is due in part to the changing height of the water table, the change in temperature and therefore evapo-transpiration, and the ease of drainage at different places down the slope.

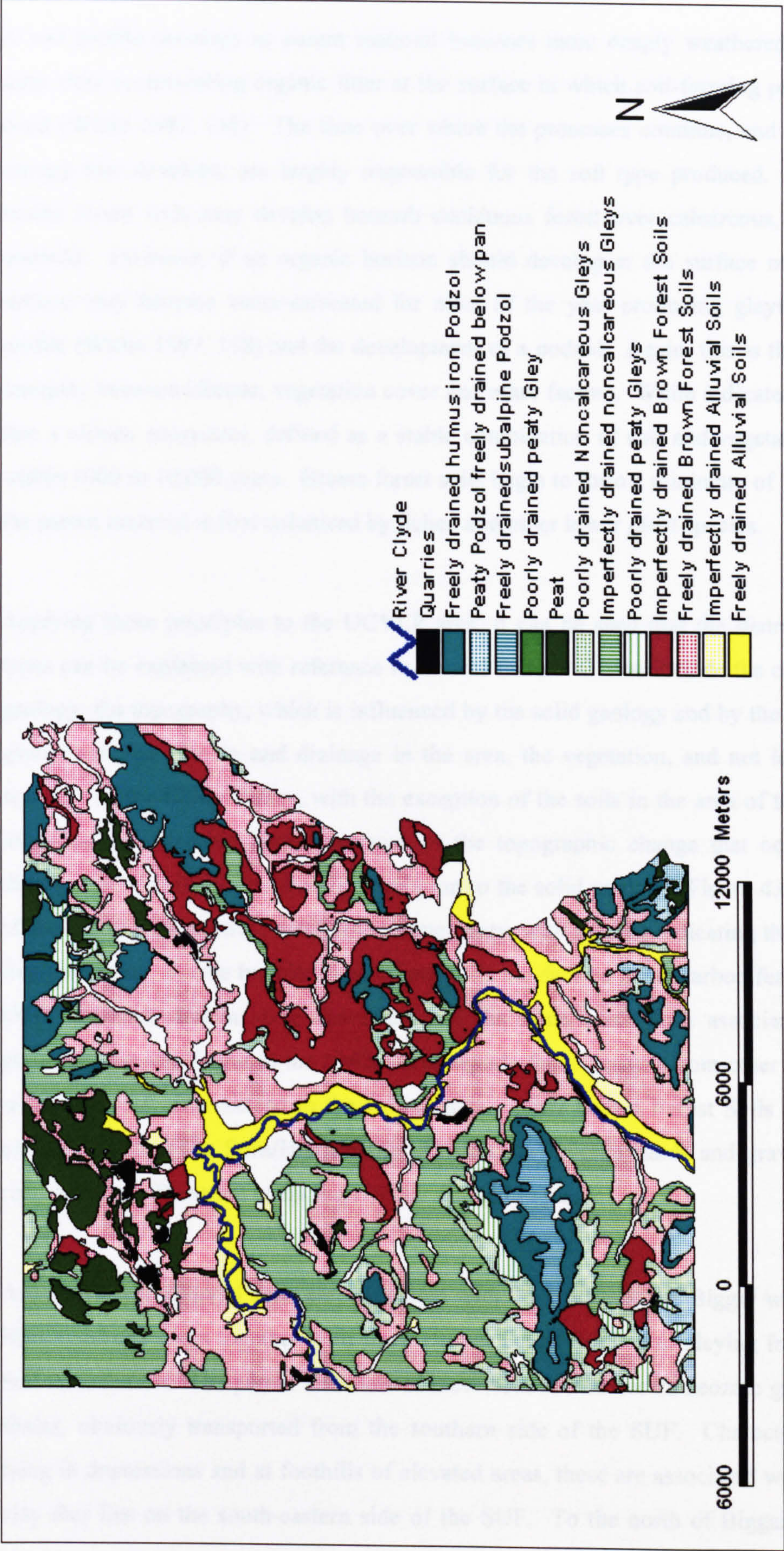


Figure 4.6:
 Distribution of soils in the study area. After Macauley 1982.

A soil profile develops as parent material becomes more deeply weathered, while at the same time accumulating organic litter at the surface in which soil-forming processes are at work (White 1987, 148). The time over which the processes continue, and the vegetation canopy that develops, are largely responsible for the soil type produced. For example, brown forest soils may develop beneath deciduous forest over calcareous, clayey parent material. However, if an organic horizon should develop at the surface of this soil, the surface may become water-saturated for most of the year producing gleying in the soil profile (White 1987, 138) and the development of a podzol. Again, this is the result of the interplay between climate, vegetation cover and other factors. White indicates (1987, 4, 78) that a climax ecosystem, defined as a stable combination of soil and vegetation, can form within 1000 to 10,000 years. Brown forest soils begin to form a minimum of 100 years after the parent material is first colonised by lichen and other lower plant species.

Applying these principles to the UCVLP area, it can be seen that the distribution of soil types can be explained with reference to several factors. These include the changes in drift geology, the topography, which is influenced by the solid geology and by the effects of past glaciations, the climate and drainage in the area, the vegetation, and not least by human activity. In the Clyde Valley, with the exception of the soils in the area of the SUF whose influence is noticeable largely because of the topographic change that occurs here, the distribution of soils bears no obvious relation to the solid geology (Figure 4.6). At the feet of the larger hills Brown Forest Soils, some peaty, with gleying indicating that they are not freely draining, overlie boulder clay. These soils are derived from Carboniferous and Upper ORS sediments and in some cases lavas of the same age. Soils associated with these geologies are also found in the lowlands alongside those derived from other Carboniferous sediments, and often extend to the valley sides. Other Brown Forest Soils from the same soil association (The Sorn/Humbie/Biel Association) overlie sands and gravels and lower river terraces. These are again imperfectly drained in places.

Around Biggar Alluvial soils are associated with the course of the Biggar water itself, and Noncalcareous gleys together with some Brown Forest Soils with gleying from the Ettrick Soil Association. The parent materials of these soils are Lower Palaeozoic greywackes and shales, obviously transported from the southern side of the SUF. Characteristic of soils lying in depressions and at foothills of elevated areas, these are associated with the boulder clay that lies on the south-eastern side of the SUF. To the north of Biggar is the largest

variation in soil units, probably a result in part of the Lower ORS age volcanics emplaced there producing a variable topography. Here the soils are predominantly Brown Forest Soils, some gleyed, together with some noncalcareous and peaty gleys. This variation in soil types continues to Black Mount, where a change in cover is seen to follow a slightly shallower north-east - south-west trend than that seen in the regional geological trend. This marks an appearance of the riverine deposits associated with the South Medwin valley. Here alluvial soils appear and those from the Eckford/Innerwick Association, which include Brown Forest Soils and humic gleys.

Landscape, Climate and Topography

Generally, the area displays the characteristic rounded landforms of a glaciated landscape (Plate 4.4). The largest hill, which dominates the view for miles around, is Tinto, standing at 707 m OD. Lying South of Tinto is Dungavel Hill at 510 m OD. The Case Studies sit within a rural landscape with the shire and market town and Royal Burgh of Lanark lying to the north-west. The other substantial settlement is the market town of Biggar, towards the south-eastern extent of the study area. This town was made a free Burgh of Barony in 1451, by King James II (Matheson 1998, 3). Apart from Carnwath, Carstairs and Carstairs Junction, the latter two of which developed and expanded with the coming of the railways to the valley, the remaining villages are relatively small, and most can be traced back to early Medieval times (Irving 1864; Sinclair 1973; Smout 1970). Certain areas, such as Symington and Libberton, have become popular with people working in Edinburgh and Glasgow, and have become 'commuter belt' areas. These are characterised by the appearance of new bungalows on the outskirts of the old villages.

Present-day settlement in the Upper Clyde valley is set against a backdrop of arable and pasture farmland, interspersed with elevated areas of rough grazing, moorland, and woodland, much of which is recent. The Forestry Commission exhibits a great deal of interest in the land around this stretch of the Clyde, and there are large areas given over to commercial coniferous forestry. Elsewhere the improvements carried out to agricultural land in the nineteenth century included the planting of shelter belts of trees. Many of the tree-lined field boundaries still evident in the area were established at this time. Extractive industries feature strongly. The industries target the glacial sand and gravel deposits, and exploit the igneous masses of rhyolite and trachyte for road stone. Significant examples of

these activities include Cairngryffe quarry, mentioned previously. Rhyolite quarried here can be seen in use on many of the smaller roads in the area giving them their characteristic red colour (Plate 4.5), which are now gradually being replaced with tarmac.

The Tinto Sand and Gravel Company represent the second example of quarrying, exploiting alluvial sand and gravel from the River Clyde. This company is active around Annieston and Thankerton (Plate 4.6), and have also been responsible for the destruction of archaeological remains, this time a number of plough-levelled sites known only from crop mark records, discovered during watching briefs or excavated pre-quarrying.



Plate 4.4:

Glaciated landforms in the study area, with an enclosed settlement in the foreground (Snaip Hill).

Plate 4.5:

The Tinto Sand and Gravel Company situated between Tinto Hill and the River Clyde in the process of quarrying sand and gravel. Rhyolite can be seen at various points along the river.



Plate 4.5:

Red rhyolite roads used to be a characteristic feature of the area.



Plate 4.6:

Tinto Sand and Gravel Company, situated between Tinto Hill and the River Clyde in the process of extracting next to a large, possibly Neolithic enclosure at Annieston. © Prof Bill Hanson.

The Soil Survey of Scotland has produced a map of climatic conditions in Scotland (The Macaulay Institute for Soil Research 1978). This map is based on the accumulated annual temperature above 5.6°C (the temperature at which vegetation growth commences) and the annual potential water deficit. These two measures of climate were used in the preparation of the map because they were considered the most suitable indications of moisture and temperature requirements for plant growth (Birse and Dry 1994, 1). The map indicates three main areas of climatic division, which correspond roughly to height above sea level, another factor taken into account during the preparation of the map (Figure 4.7 and Table 4.1 a) and b), which explain the climatic divisions, only three of which appear in Figure 4.7). There is a central belt that follows the course of the river Clyde through the study area, which is described as “Fairly warm moist lowland and foothill” (Macaulay 1978). All of the Case Studies lie within this central area. This division has been combined in Figure 4.7 with a second originally mapped separately, described as “Fairly warm rather wet lowland and foothill”. This encompasses the area in the north-west quadrant, north-east along the Medwin Valley, the area to the north and north-east of Biggar, south-west of Symington and to the north of Tinto. A smaller proportion of the study area is described as being “cold wet upland”. Not surprisingly, this division describes the topographic high of Tinto Hill. The remaining land comes under the category of “Cold, rather wet lowland, foothill and upland”.

Much of the farming activity in the area today involves rotation of cereal, mainly barley, and grass crops. The farming tends to be mixed, with a preference for sheep and dairy farming in the south-west and a greater reliance on arable in the central belt around the Clyde itself. The rotation tends to be a five-year one with two to four years of grass for silage and pasture and one or two years of arable. Rarely some farmers include a root crop in the rotation, and some landowners are returning fields to mixed forestry under the woodland regeneration scheme.

The climatic map helps to refine the idea that the climate, and in particular the climate as it affects plant growth, is affected by altitude, topography and morphology of the landscape. The River Clyde in its low-lying river valley is the most significant influence upon the UCVLP area in this respect, with its warmer, moist environment having an effect on the growth of food crops. By contrast we find that the upland environment of Tinto is the least hospitable to vegetation and to human settlement. This information begins to give an insight into why people settled the land where they have and the uses to which it has been, or is

being put. It also gives the final piece of information about the distribution of soil types in the study area.

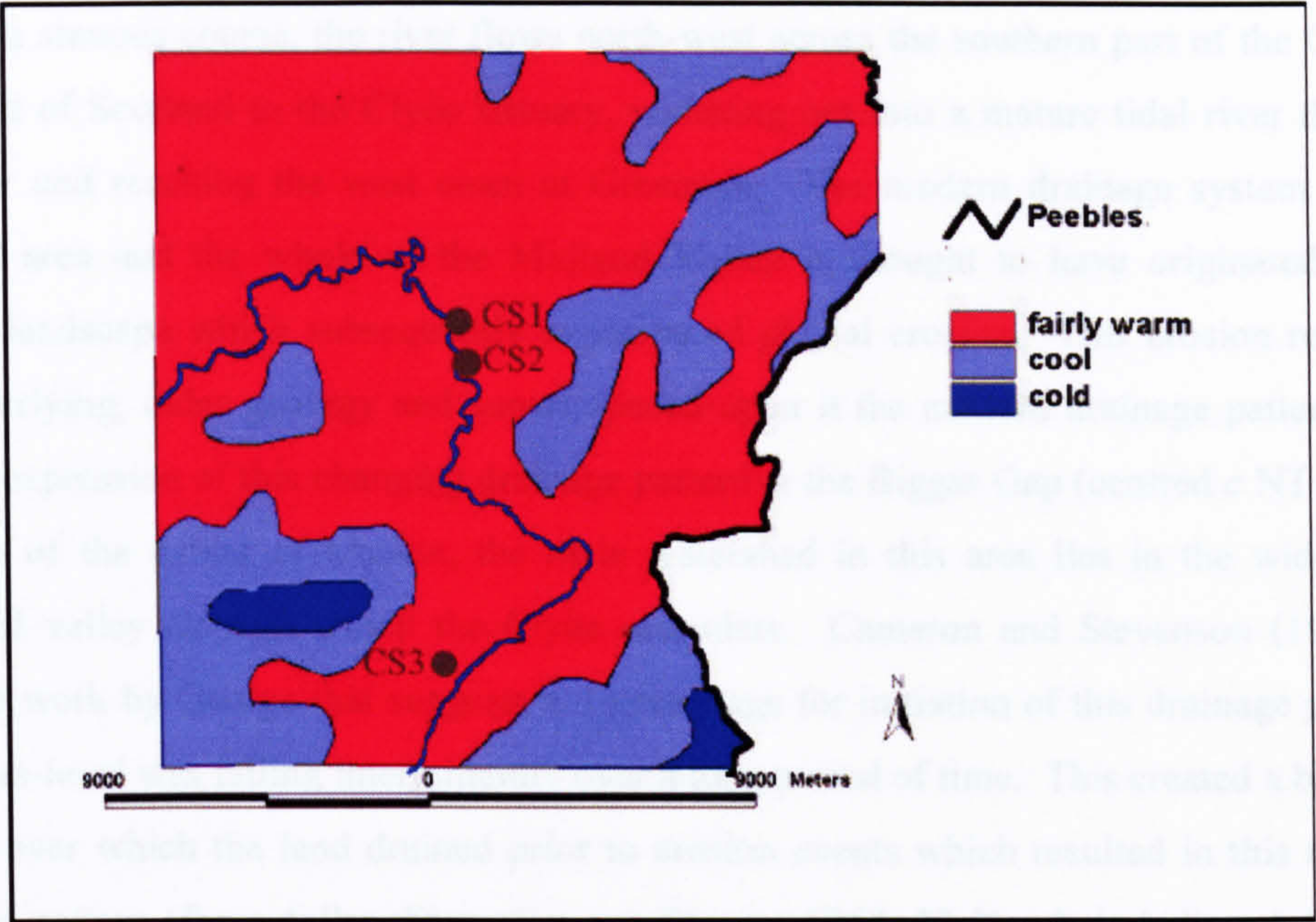


Figure 4.7:
Climatic divisions in the study area (based on Macaulay 1978).

Table 4.1a)

Division	Accumulated Temperature Range (day degrees C)	Potential Water Deficit (mm)	Height above sea level (m)
LM	1100-1375	25-50	0-400
LR	1100-1375	0-25	0-400
SV	550-825	0	400-800
MR	825-1100	0-25	0-800

Table 4.1b)

Division	Description	UCVLP Example
LM	Fairly warm moist lowland and foothill	Central Clyde River course: “Fairly Warm” from Figure 4.7
LR	Fairly warm rather wet lowland and foothill	Medwin Valley: “Fairly Warm” from Figure 4.7
SV	Cold wet upland	Topographic highs, e.g. Tinto; Highlands: “Cold” from Figure 4.7 associated with the SUF
MR	Cool, rather wet lowland, foothill and upland	Remaining area: “Cool” from Figure 4.7

Today, the Clyde rises from a twin source in the Lowther Hills in the central part of the Southern Uplands. The river enters the Midland Valley, and the UCVLP area, near Lamington. From Lanark at the western extent of the study area, through which the Clyde follows a sinuous course, the river flows north-west across the southern part of the Central Coalfield of Scotland to the Clyde Estuary, widening out into a mature tidal river through Glasgow and reaching the west coast at Greenock. The modern drainage system of the UCVLP area and the whole of the Midland Valley is thought to have originated in an ancient landscape which subsequently experienced glacial erosion. This erosion revealed the underlying, older geology and superimposed upon it the modern drainage patterns. A surface expression of this changing drainage pattern is the Biggar Gap (centred c NT 0737). Because of the extent of erosion, the main watershed in this area lies in the wide, flat-bottomed valley through which the Clyde meanders. Cameron and Stevenson (1985, 4) describe work by George that suggests a Tertiary age for initiation of this drainage pattern, as the sea-level was falling intermittently over a long period of time. This created a benched surface over which the land drained prior to erosion events which resulted in this modern drainage pattern (for a fuller discussion see Sissons 1967, 22-8). It is believed that the Clyde originally flowed through the Biggar Gap into the Tweed. The present course through Clydesdale is a result of a process known as River Capture. This process is also thought to have occurred around Carstairs, where the streams were captured by the Clyde previously having flowed south-eastwards into the Tweed (Cameron & Stevenson 1985, 3).

Land-Use

The River Clyde impacts greatly on the area. Its sinuous course through the land means that it affects the area in terms of climate, as discussed above, and of settlement. The archaeological remains recorded along the extensive river valley and its terraces indicate that it must have been attractive to prehistoric settlers. Marshy low-lying land close to the river would have attracted a variety of wild birds and animals which could be exploited for food, and the higher terraces, the result of the glaciations described above, would provide suitable areas for settlement and agricultural activities, leaving the higher land and hill tops for grazing livestock in summer and for defensive positions when needed. The earliest human activity in the UCVLP area is identified from lithic scatters located during fieldwalking and is of Mesolithic date. Later prehistoric activity is recorded in aerial photographs of crop markings and extant monuments. Distributions of sites and finds from

the UCVLP database have been used to produce maps that allow the temporal evolution of the area to be investigated. This is discussed fully in the UCVLP report (Hanson and Sharpe in prep).

The sixteenth century pattern of settlement depicted on Pont's maps is little changed today (Stone 1991, 50-3) and has set the scene for the development of the modern landscape. Settlement in the 1500's appears to have been concentrated in the eastern half of the study area and favours the low-lying areas, especially to the east of the Clyde where the land is under arable production today, indicating that the settlement was directed by easily cultivated, fertile soils with longer growing seasons. As Stone suggested, the settlement pattern also appears to be influenced by proximity to the river Clyde and its tributaries. These factors combine to give a fairly dense settlement pattern towards the centre of the study area in the south, where the flood plain of the Clyde is relatively narrow between Dungavel Hill to the west and the high land associated with the SUF to the east. From here the river valley widens out around Coulter and Symington to the north, into a funnel shape, allowing a more dispersed pattern of settlement. Here maps indicate that the sixteenth century settlements were regularly spaced with the majority lying in the north-east of the study area above Biggar. The distribution of the settlements again suggests a development in proximity to watercourses or along routes leading to either Biggar or Lanark. The positions of the three Case Studies for this thesis are no exception in suggesting the importance of the River Clyde for settlement, all lying within 500 m of the river.

4.4 The Case Studies

The three sites chosen for this study are all crop mark sites and all produce at least one crop mark suggestive of a ditched enclosure that is circular, or approximately so. The sites were subject to varying depths of investigation, dictated mainly by the farmers' willingness to allow invasive examination to be carried out, which is a problem pertinent to the archaeological investigation of sites generally. Consequently, all of the site investigations comprise an aerial component, varying amounts of geophysical survey work, and soil sampling for later analysis. At two of the three sites trial excavations were also undertaken. Table 4.1 summarises the environmental settings of each of the sites, which were instrumental in their selection.

Case Study 1: Craigie Burn Enclosure

Case Study 1 (NGR: NS 98844185, NMRS no: NS94SE 19) lays in a field 500 m to the south of Townhead Farm, itself c 1.4 km to the south of the village of Libberton. Ovate crop marks appear over what is considered to be either a henge or a later prehistoric settlement, comprising two opposed entrances and double ditches separated by two banks (Plate 4.7). In some places a third bank is occasionally visible. The site, which lies in a large field created from three smaller ones whose boundaries now also appear as cropmarks, takes its name from the burn that flows 500 m to the south-west into the River Clyde.

The first edition of the Ordnance Survey (OS) map of the area describes the site, then known as “Camp Craigie”, as a curling pond. The site lies on roughly level ground which breaks away steeply to the west and south, falling down to the River Clyde which winds past the Burnfoot Farm enclosures (Case Study 2) only 1.3 km to the south-east. The banks and ditches of the enclosure are clearly noticeable on the ground from the centre of the site. The centre of the enclosure forms a large, bowl-shaped depression, with the outer banks barely higher than the surrounding ground, but still in places the ground rises a good 1.5 m from interior to exterior. The visual impact of the enclosure was enhanced by the differential growth of the grass crop in the field during the 1999 field season. Over the medial ditch in particular the grass was a darker green than that growing over the banks, interior and rest of the field.

In addition to the examination of the aerial photographic record available for this site, a programme of geophysical survey was completed in 1999. The results of this and survey at the other sites are presented in Chapter 5. After being under grass for some four years, the field in which the enclosure lies was ploughed in April 2000 in preparation for a barley crop to be sown. Before ploughing, permission was granted to carry out test pitting across the banks and ditches of the enclosure. This allowed soil samples to be collected from secure contexts and the responses to the underlying features to be tied in and examined more closely. After ploughing, the site was fieldwalked as part of the UCVLP. In addition, a transect across the east side of the enclosure that corresponded to geophysical anomalies recorded earlier was sampled using a corkscrew auger. The soils collected from the sampling points were used in the barley growth experiments and soil analyses detailed in Chapter 3.

Table 4.2: Summary of the Environmental Setting and Site Information for the Three Case Study Sites

Site Name	Solid Geology	Drift Geology	Soil Type	Topographic Setting	Climatic Category	No Enclosures
Case Study 1: Craigie Burn Enclosure	Upper sediments*	ORS	Free draining Brown Forest Soils	Upper river terrace	Warm lowland foothill moist and	1
Case Study 2: Burnfoot Farm Enclosures	Andesite & Basalt with upper sediments* at N faulted contact	ORS	Free-draining Brown Forest Soils; Alluvial soils at R. Clyde side	Lower river terrace	Warm lowland foothill moist and	6
Case Study 3: Chesterhall Parks Enclosures	Lower sediments**	ORS	Free-draining Brown Forest Soils (but see below)	Lower river terrace	Warm lowland foothill moist and	Up to 9

* sandstones, limestones; ** greywackes



Plate 4.7:

Case Study 1 from the air. © RCAHMS.

Case Study 2: Burnfoot Farm Enclosures

The second site lies *c* 1.3 m south-east of the Craigie Burn enclosure at Burnfoot Farm (NGR: NS 99184050; NMRS no: NS94SE 32), which lies 2 km to the south of the village of Libberton. Lying in the field adjacent to the modern farm buildings, this site reveals a series of at least four enclosures appearing as cropmarks (Plate 4.8), some of which were also identified from geophysical survey results (Chapter 5; Hanson and Sharpe 2001). From undulating higher ground in the east, the ground descends to the River Clyde flood plain in the west, with the river meandering past around 40m from the westernmost field boundary. Although it appears flat in the aerial photographs, the field in fact undergoes fairly large topographic changes. The eastern half is occupied by a series of three rounded topographic highs of fluvioglacial origin. The two large enclosures are situated upon two of the rises in what appears to have been a deliberate exploitation of the natural features.

The field was under grass, had not been ploughed since around 1995 and was not ploughed during the duration of the UCVLP. Because the field is in constant agricultural use, the farm owner, Mr David Russell, was unhappy for much more than non-invasive survey to be undertaken, a common situation arising during archaeological fieldwork. For this reason there has been no excavation at the site. Instead, the field has been surveyed over almost its entire length using magnetic and resistivity techniques and a small area (20 m x 60 m) sampled using a corkscrew auger. The results of these investigations, together with information from aerial reconnaissance, are presented in Chapter 5.

The site lies over the lower reaches of the two modern drains. At the north-western



Plate 4.8:

Case Study 2 from the air. © Prof Bill Hanson.

Case Study 3: Chesterhall Parks Enclosures

Chesterhall Parks Farm is the most southerly of the three sites. This site is situated on land belonging to Chesterhall Parks Farm (NGR: NS 977324. NMRS no: NS93SE 34), owned by the Maxwell-Stuarts of Lamington and tenanted by Mr and Mrs McCulloch. The site comprises a series of small circular enclosures that appear as cropmarks in grass (Plate 4.9), clustered over the area of two modern fields. The site lies on a river terrace above the present River Clyde flood plain. Bounding the modern field, and conceivably truncating a

continuation of the site, is the main railway line linking Scotland and England, destined for Carstairs Junction some 13 km to the north-west. Disregarding the steep railway embankment and crossing a small burn draining into the Clyde, now diverted beneath the railway, the land gently descends onto the flat flood plain. Despite the soils at this site being classified as freely draining brown forest soils (Table 4.1), the landowner's description, which has been confirmed by excavation, is of tenacious and poorly drained clay soils.

The site itself lies over the lower reaches of the two modern fields. At the north-western extent of the site the land rises quite steeply up to a second terrace. In total, up to 9 enclosures have been recorded on aerial photographs from different reconnaissance flights. The enclosures, which are closely grouped together, are circular on plan and vary in size and in the number of ditches that surround them (1 – 3), the smaller enclosures tending to have fewer ditches.

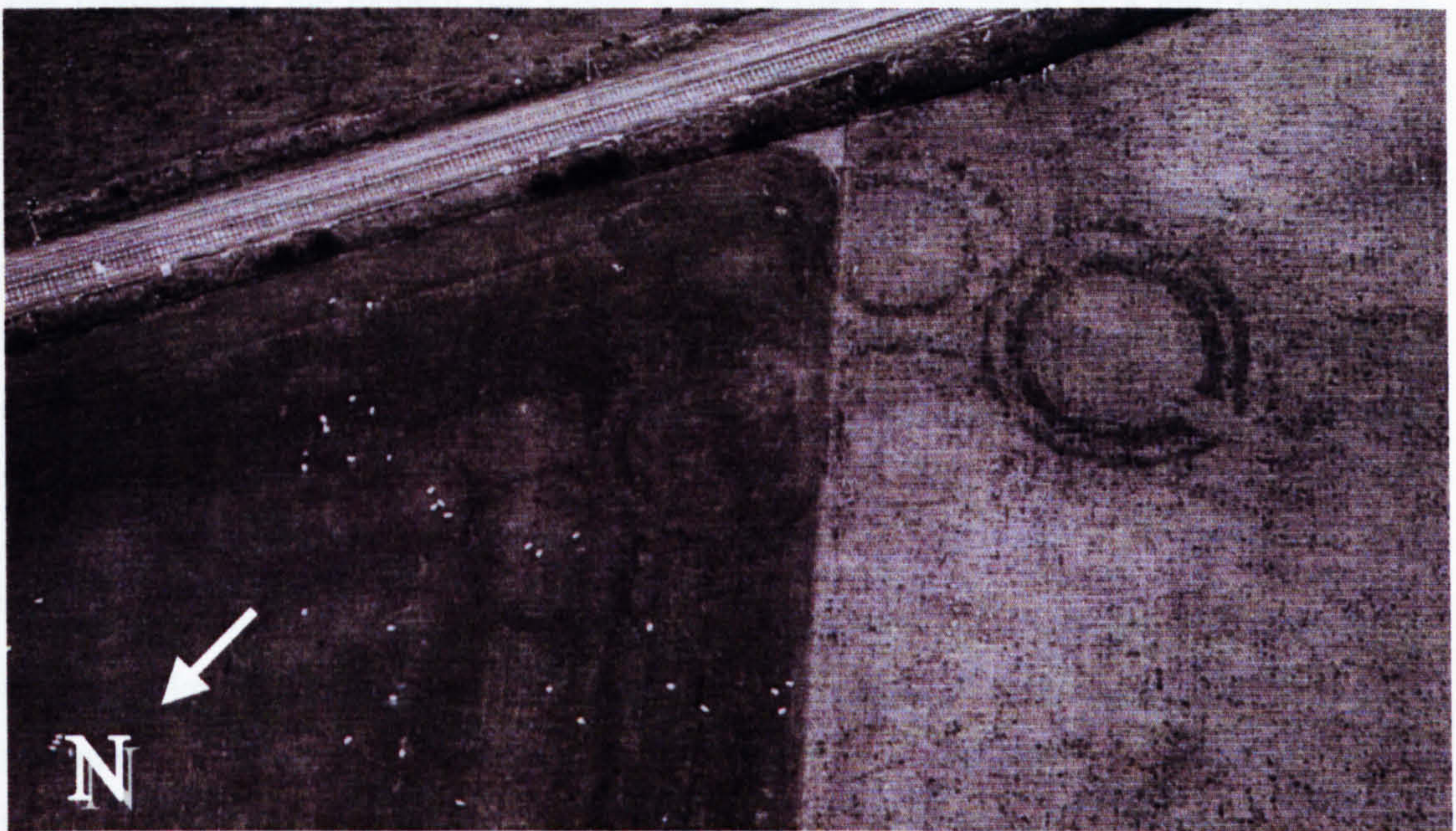


Plate 4.9:

Case Study 3 from the air. © Prof Bill Hanson.

Investigation at this site has taken the form of examination of aerial photographs, geophysical survey, and the most extensive of the trial excavations undertaken as part of the UCVLP. In this case it will be seen that the geophysical surveys were not very successful, which is unusual for the sites in the UCVLP area. The analysis of the soil samples taken

during the excavations will shed light on why this is the case. The examination of the data from this case study is a good example of why apparently 'negative' results from field investigation can in some respects prove to be more valuable than results that would traditionally be seen as a success. This site represents the essential comparator for the preceding case studies, which produced coherent geophysical results and reliable cropmarks. The Chesterhall enclosures have geophysical responses that are difficult to resolve and a limited aerial photographic record, suggesting sporadic appearance of cropmarkings. This suggests that any geochemical differences associated with the archaeological features that are detected here relative to the first two sites are likely to be important to the definition of both types of anomaly, and so play a pivotal role in site detection.

4.5 Summary of Chapter 4

The landscape of the modern day Upper Clyde Valley is the result of a long evolution of geology, drainage patterns, climate, vegetation cover and human interactions. Each factor has been shown to be intimately linked. The combination of the natural forces of this evolution has influenced the places that humans have used and adapted throughout the time that they have inhabited the area. This exploitation of the habitats and resources of the area has left its mark on the landscape in the form of archaeological remains. Three of the sites examined in the UCVLP area were chosen as targets for the application of the hypotheses under investigation for this thesis.

The archaeological remains surviving today are a product in part of the continued use to which the land has been put. The whole process, natural and anthropogenic, of landscape formation has implications for the preservation of features and information, and our ability to retrieve it. This leads to the question of what evidence of activity is preserved in and beneath the topsoils, and how much of this can be accessed remotely? What information can we gather chemically and geophysically from the media that make up the sites, and what physical and chemical conditions exist that allow us to detect sites from aerial photographs? To answer these questions, we must take the theoretical basis for the geophysical and crop responses introduced in Chapter 2, and the methodologies presented in chapter 3, and apply them to the sites described in this chapter. The work resulting from this application of the theoretical to the practical is presented in chapter 5. The investigation of the responses from

the three Case Studies is described, and in Chapter 7 all of the work undertaken for this thesis is drawn together for analysis and discussion.

Chapter 5: Case Studies: The Remotely Sensed Evidence

5.1 Introduction

This chapter looks at the results of remotely sensed data from the three Case Studies introduced in Chapter 4. The three sites chosen for the study (Figure 4.1) were subject to varying depths of investigation, which was mainly dictated by the farmers' willingness to allow disruption to the field in which the site lay. Consequently, all of the site investigations comprise an aerial component, and varying amounts of geophysical survey work. There are also soil samples available for analysis from each of the sites, and Case Studies 1 and 3 have information about the nature of the buried remains, gathered during trial excavation. The choice of sites was based upon the feature types present at each, together with the way in which each of the techniques responded to them. The three sites comprise varying numbers of circular to ovate enclosures which are defined by ditches, and belong to the prehistoric period. None of the sites contain extant remains, although at Craigie Burn enclosure (Case Study 1) it is easy to see the remains of the ploughed out banks and ditches. For the first two sites there is an extensive aerial photographic archive, suggesting that crop marks appear regularly above them, and the results of geophysical investigations there correlate very closely with the patterns of altered crop growth recorded aerially. At the third site, however, not only is there a limited record of crop mark formation, but equally geophysical responses did not appear to coincide with the features appearing as crop marks, and did not assist interpretation of the site, although they did help to locate certain features for excavation purposes. This site was the exception to the rule in that it did not respond positively to geophysical investigation in contrast to every other site examined as part of the UCVLP. It was instead a valuable comparator for investigating why, generally, arable crop responses and geophysical anomalies tend to correlate very closely at least in this part of Southern Scotland.

The full details of the work carried out at each site are given in the UCVLP report (Hanson and Sharpe in prep). Here, a comparison is made between the aerial information gathered at each site and the results of geophysical survey, concentrating on how much correlation there is for feature detection between techniques. For ease of comparison the transcriptions made of each site has been overlaid on interpretative plots of the geophysical data in ArcView

GIS. In places, particularly at Case Study 3, there is an offset between the responses. This is due to inaccurate location of the features on the rectified plans of aerial photographs due to a lack of control points (see Chapter 3). For this reason, and the confused nature of the pictures sometimes produced by the overlays, the interpretative plots derived from them, rather than the GIS views themselves, have been used for illustrative purposes throughout.

5.2 Case Study 1: Craigie Burn Enclosure

Introduction

The enclosure at Craigie Burn lies on land attached to Townhead farmhouse, which is situated around 500 m to the north (Figure 4.1). The site takes its name from the burn flowing south-west, just 500 m of the enclosure into the River Clyde. Around 1.3 km to the south-east the river winds past Burnfoot Farm (Case Study 2). The enclosure is sited on elevated land, relative to Case Study 2, and lies upon Upper ORS sediments overlain by boulder clays (see Table 4.2), with a soil cover of freely draining brown forest soils that have a long history of cultivation for mixed arable farming. As has come to be expected from this geological setting (Hanson and Sharpe in prep), the geophysical survey techniques were successful in revealing the enclosure relative to its background.

This site was subject to aerial and geophysical prospection methods and, in addition to soil samples being taken using a corkscrew auger, a limited amount of test-pitting was carried out (Hanson and Sharpe in prep). Augured soil samples were taken from the east side of the geophysical survey grid (Figure 5.1) and these, together with soil samples from the excavations, were used in Experiment 3, the methodology of which was discussed in Chapter 3, and the results presented in Chapter 6.

Aerial Photography

Craigie Burn is one of the most reliable sites in the UCVLP area for the appearance of crop marks; if it is not visible during a sortie, it is unlikely that many other sites in the area will be visible (Prof Bill Hanson, pers comm.). That the site is very conducive to producing crop marks was obvious during the fieldwork seasons when differential growth of the grass crop over the ditches was clearly visible from the ground. This enclosure has an extensive aerial

photographic archive, held at RCAHMS (Plate 4.7, 5.1), and, like the Burnfoot enclosures, has also been photographed by CUCAP fliers and by Prof Bill Hanson.

Unlike Case Studies 2 and 3, this site comprises one single enclosure, although a second enclosure, not considered further here, appears occasionally on the aerial photographs. It lies *c* 150 m to the north-west of the main enclosure, and in most photographs lacks sufficient control points to allow transcription.

The photographic archive spans the period from 1967 up to the most recently catalogued photographs, at the time of writing, from 1995. Table 5.1 lists the dates of photography and examines the degree to which the site shows, and includes a number of photographs from the CUCAP collection that are not dated. The site is variously described by the RCAHMS as an earthwork (1967 to 1988), and a possible henge (1989 onwards).

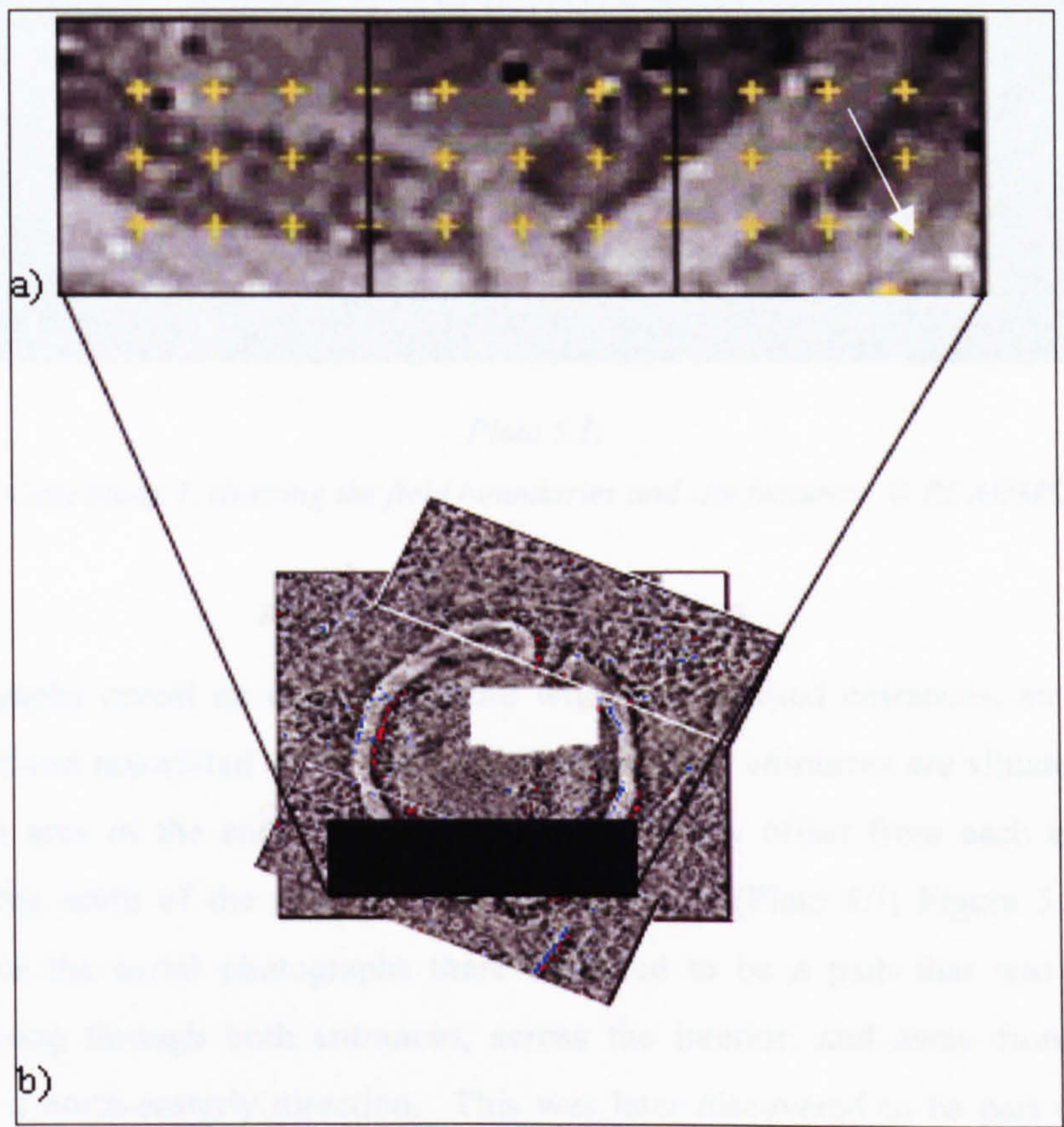


Figure 5.1:
Location of soil sampling points at Case Study 1 (a) relative to the survey grid (b).



Plate 5.1:

Case Study 1, showing the field boundaries and site features. © RCAHMS.

The photographs reveal an ovate enclosure with two opposed entrances, an internal and medial ditch and associated outer and medial banks. The entrances are situated in the east and western arcs of the enclosure perimeter, are slightly offset from each other and lay slightly to the north of the centre-line of the enclosure (Plate 4.7; Figure 5.1). On first inspection of the aerial photographs there appeared to be a path that was occasionally visible, passing through both entrances, across the interior, and away from the eastern entrance in a north-easterly direction. This was later discovered to be part of a drainage system that had been installed to try to remove the standing water that often lies in the enclosure interior. This is clearly illustrated in the aerial photograph taken by the RCAHMS (Plate 4.7).

Table 5.1: Aerial Reconnaissance results over Case Study 1 from c 1967 to 1995

Year	Source	Taken From	Outer Bank	Outer Ditch	Inner Bank	Inner Ditch	Internal Features	Drains	Other Marks	2nd Enclosure
NA	CUCAP	E	~Y	Y	Y	Y	Y	~Y	N	NA
NA	CUCAP	SE	Y	Y	Y	Y	N	Y	N	N
NA	CUCAP	W	N	Y	Y	Y	N	N	N	NA
NA	CUCAP	N	~Y	Y	Y	Y	N	Y	N	NA
NA	CUCAP	S	~Y	Y	Y	Y	~Y	Y	N	NA
NA	CUCAP	W	Y	Y	Y	~y	N	Y	N	~Y
1967	CUCAP	SE	N	Y	Y	y	N	Y	N	NA
1967	CUCAP	S	~Y	Y	Y	y	N	Y	N	NA
1976	RCAHMS	NE	N	Y	Y	~y	N	N	N	NA
1977	RCAHMS	NE	Y	Y	Y	y	~Y	Y	N	NA
1978	RCAHMS	SE	~Y	Y	Y	~y	~Y	Y	N	NA
1988	RCAHMS	W	~Y	Y	Y	Y	~Y	Y	N	NA
1988	RCAHMS	E	~Y	Y	Y	Y	~Y	Y	N	N
1989	RCAHMS	NW	Y	Y	Y	~y	Y	~Y	N	NA
1989	RCAHMS	NW	Y	Y	Y	Y	~Y	~Y	N	NA
1991	RCAHMS	NE	N	Y	Y	~Y	N	~Y	Y	N
1992	RCAHMS	NW	N	Y	Y	Y	~Y	N	N	NA
1992	RCAHMS	E	Y	Y	Y	Y	Y	Y	N	Y
1993	RCAHMS	SW	N	Y	Y	Y	N	N	N	NA
1993	RCAHMS	SE	Y	Y	Y	~Y	N	N	N	~Y
1995	RCAHMS	NW	N	Y	Y	Y	~Y	N	Y	Y
1995	RCAHMS	W	N	Y	Y	Y	~Y	N	Y	~Y
1995	RCAHMS	NNW	~Y	Y	Y	Y	Y	Y	Y	NA
1995	RCAHMS	SE	N	Y	~Y	N	Y	N	Y	NA
1995	RCAHMS	E	N	~Y	Y	N	Y	NA	Y	Y

A visit to the site in early 2004 revealed that the worst affected west side of the interior had been covered with a thick layer of topsoil to attempt to remedy the flooding situation, with a limited degree of success. Other than this, there has been little more than fleeting glances of possible hut circles appearing in the interior (K Brophy Pers comm.). The first edition of the Ordnance Survey map indicates that the enclosure was then in use as a curling pond. So, given the extensive drainage of the site and this later recreational use, which would be likely to encourage the deposition of silt, not to mention the habit of adding clay linings to such ponds, it is not surprising that the interior of the enclosure appears to be devoid of features. Whilst there is a high probability of good preservation of any subsurface features present below any sediment build-up, installation of drains is likely to have had a detrimental effect.

Interpretation of the Aerial Photography

The possible henge at Craigie Burn is interpreted, and confirmed by trial excavation (Hanson and Sharpe in prep), as having outer and medial banks and medial and inner ditches based on the crop marks (Figure 5.2). As with the initial interpretation of most aerial photographic information, this identification of ditched and banked features is based on the colour of the crop marks. Those plants growing over the banks tend to have a lighter appearance and those over the ditches a darker green colour. In this instance, a visit to the site on the ground confirmed this interpretation, even in the grass crop.

The outer bank tends to be the least obvious of the four perimeter features, with the inner ditch being the second least likely to appear (see Table 5.1). The medial ditch and inner bank appear most consistently and are still visible in photographs with the least clarity of markings, such as those taken in 1976, 1991, 1993 and 1995 (NMRS box file archive of oblique aerial photographs). Table 5.1 indicates that the clarity of the crop mark does depend in part on the angle from which the photograph was taken. Plough-truncation is considered to be responsible for the poor appearance of the outer bank on remotely sensed data. This outermost feature, standing highest topographically, would suffer the impact of the plough most. Eventually as it became levelled, the bank material would be redeposited downslope over the interior of the enclosure, helping to protect the inner features from as much damage. Hence, the apparently better preservation of the medial ditch and bank, with perhaps the inner ditch appearing less sharply due to a deeper ploughsoil cover.

Closer examination of the site's aerial photographic record in the light of the geophysical survey results suggested that the intermittent appearance of the internal ditch may be due to it actually being a series of pits, presumably quarry pits providing material for the enclosure banks, rather than a continuous ditch. Limited trial excavation tended to confirm this interpretation (Hanson and Sharpe in prep), although larger scale excavation would be required for full confirmation. The irregular nature of the internal ditch is especially noticeable against the smoothly defined lines of the medial ditch and bank. The effect is best seen in photographs taken in 1989, 1992 and 1995 (NMRS oblique aerial photographic archive). The aerial photography together with the geophysical survey results suggests that the western terminal of the southern medial ditch is different to the other three terminals. Indeed, the morphology of the two opposed entrances can be seen to differ in all the remotely sensed data.

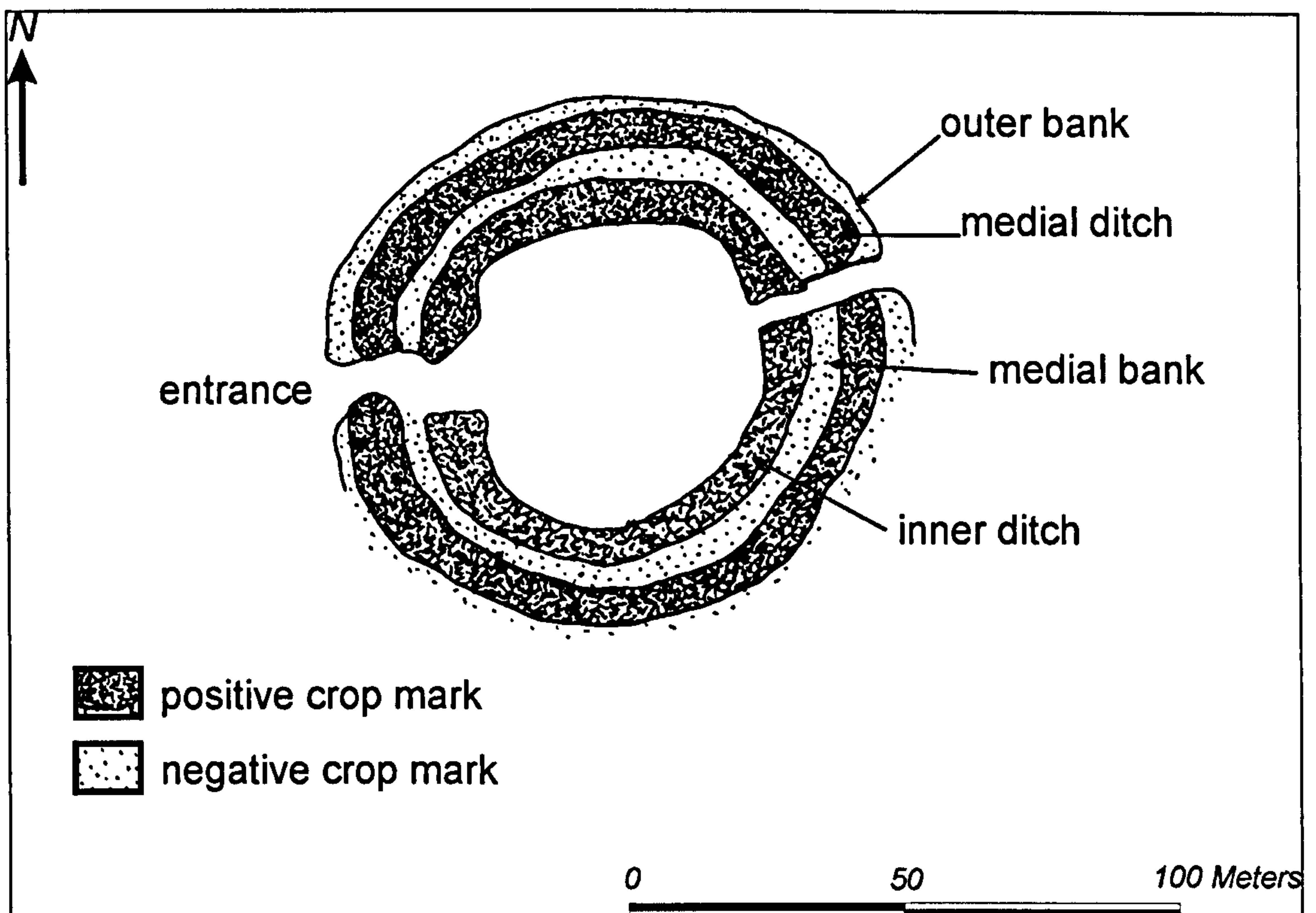


Figure 5.2:

Interpretation of the aerial photographic transcription annotated with the features to be discussed.

Geophysical Survey

The surveys of the enclosure were completed over a period of two years. In the first year (1998) the whole enclosure was covered using both geophysical techniques at the standard sampling density of 1.0 m, over 20 m grids. In 1999 a close interval magnetic survey of the interior was conducted in an attempt to detect any features that may have been associated with activity at the site. At this time the sampling density was increased to 0.5 m and the whole of the interior was surveyed, the area of standing water having dried up temporarily. The survey plots are presented below in Figures 5.3 to 5.5.

The Survey Plots

The resistivity survey data (Figure 5.3) has clearly detected the enclosure due to the changes in resistive properties of the materials comprising the banks and ditches. The blank central portion marks the area of standing water. The effect of the waterlogging on the passage of the current applied during the survey is clearly indicated by the patches of very low

resistance appearing in blue around the blank area of dummy readings. In all of the plots the remains of the old field boundaries are clearly visible surrounding the enclosure.

On Figure 5.3 the data was processed using only the cosmetic smoothing effect of interpolation in both the x- and y-directions to remove the slightly pixellated appearance of the data. This is common to most of the data collected due to the coarse 1 m sampling intervals used. This figure, as with all the grey-scale plots presented, uses a Geoplot palette that highlights maximum (red) and minimum (blue) readings, which assist in interpretation.

The magnetic survey data for the whole enclosure (Figure 5.4) and the interior (Figure 5.5) were processed by despiking and using the zero mean grid function to remove edge effects in the data, and the full area survey was then interpolated as described for the resistivity data.

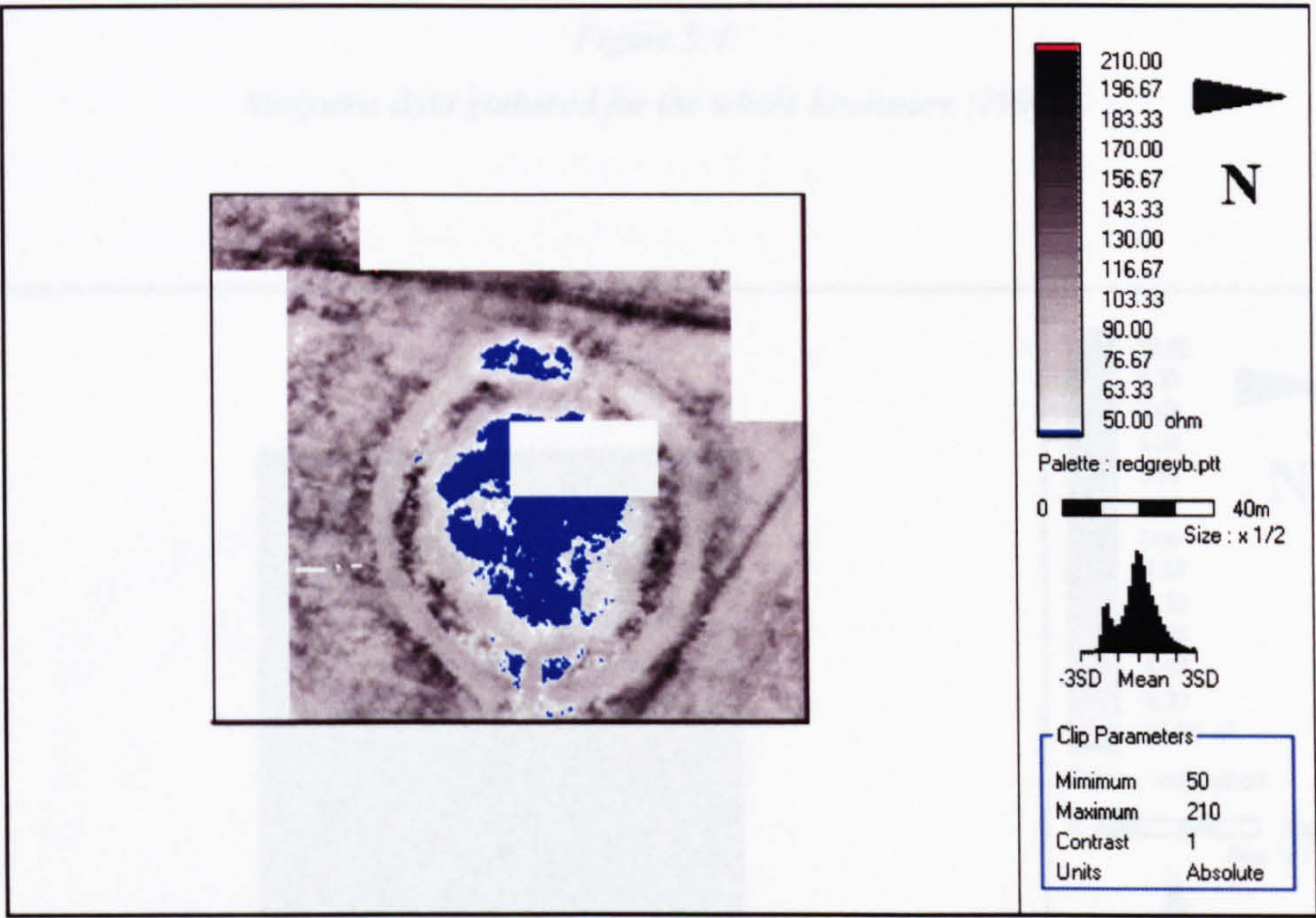


Figure 5.3:
Resistivity data from the enclosure.

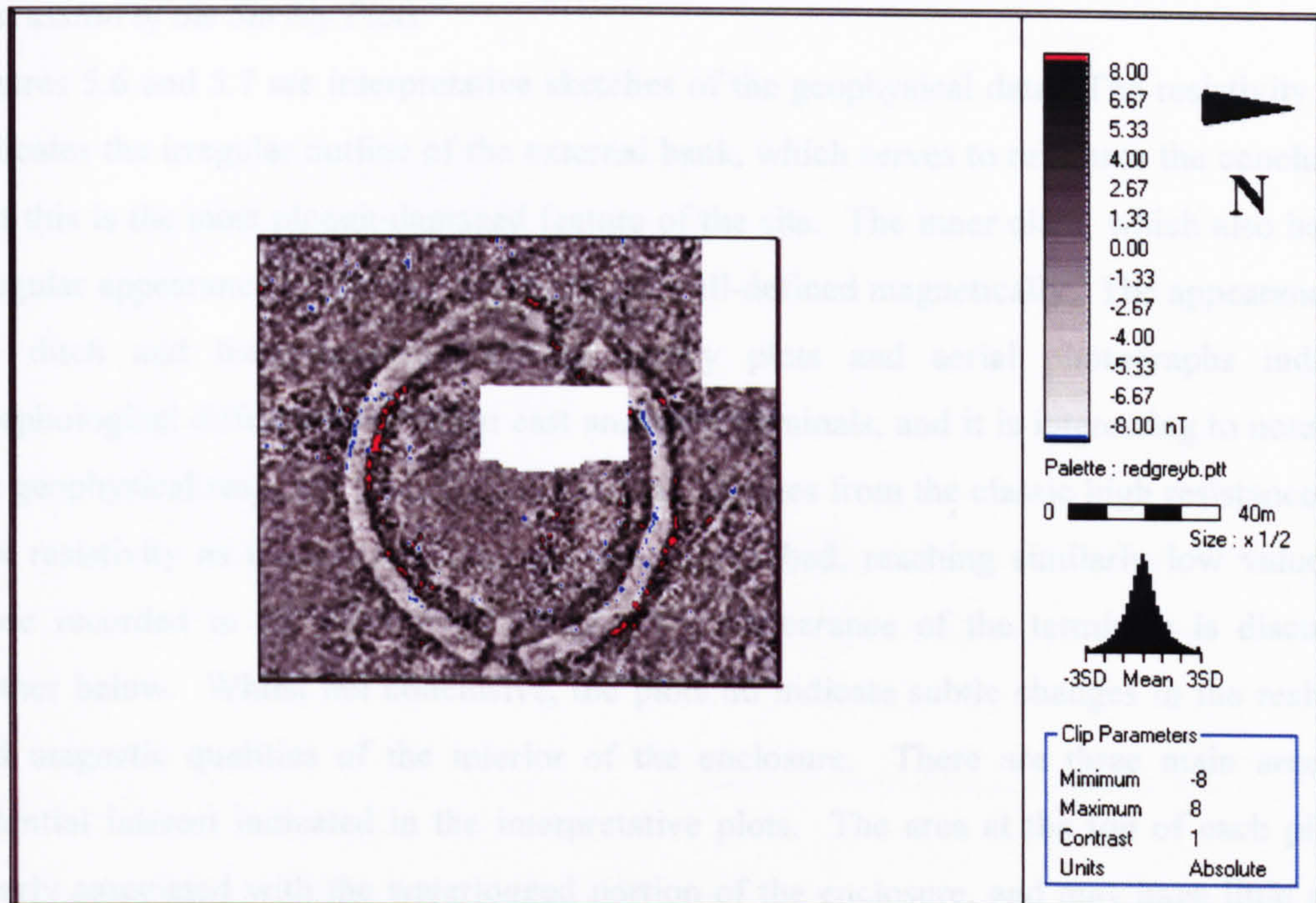


Figure 5.4:
Magnetic data gathered for the whole Enclosure (1998).

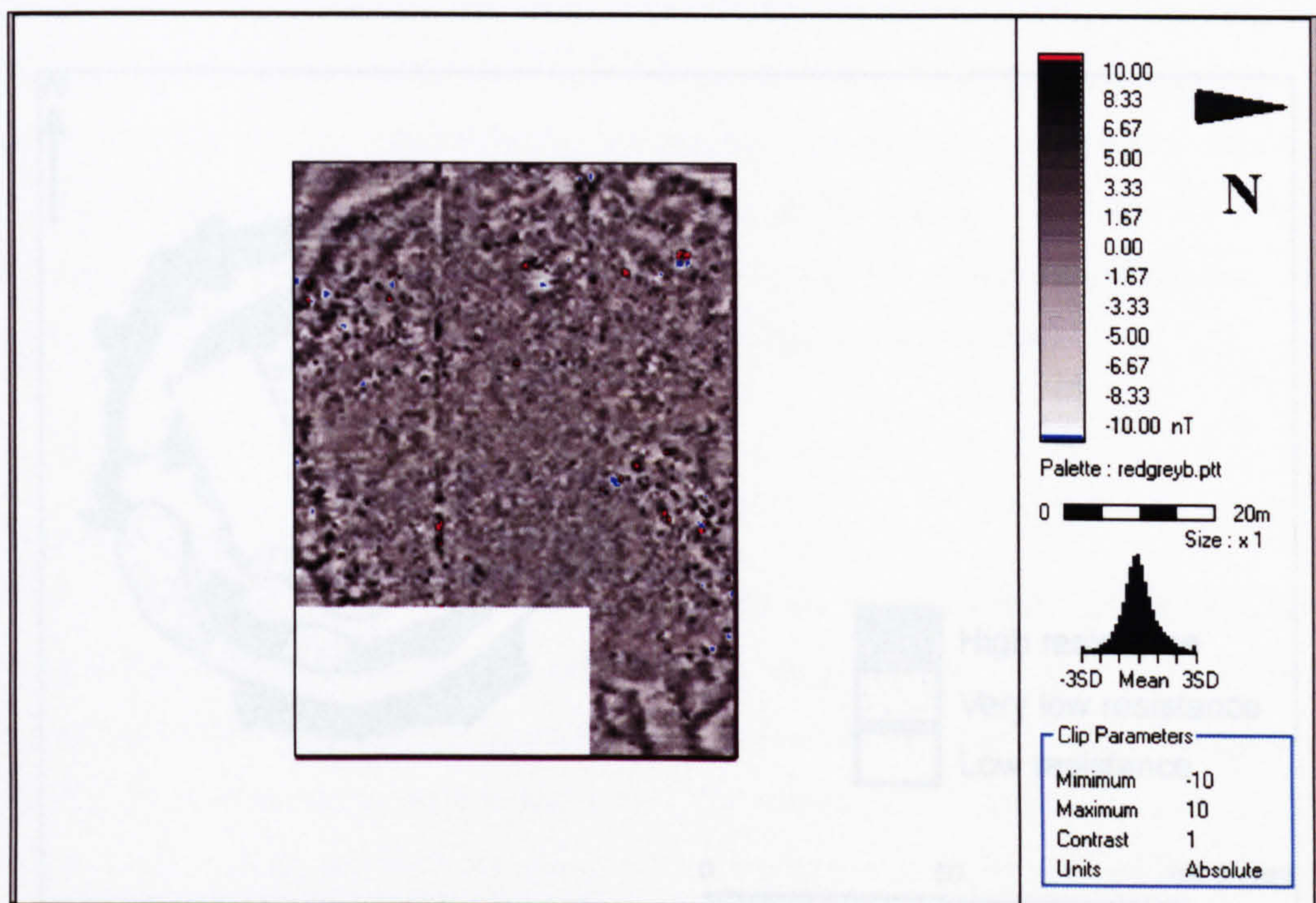


Figure 5.5:
The close interval survey plot from Case study 1 interior (1999).

Discussion of the Survey Plots

Figures 5.6 and 5.7 are interpretative sketches of the geophysical data. The resistivity data indicates the irregular outline of the external bank, which serves to reinforce the conclusion that this is the most plough-damaged feature of the site. The inner ditch, which also has an irregular appearance in the resistivity data, is well-defined magnetically. The appearance of the ditch and bank terminals in the survey plots and aerial photographs indicate morphological differences between east and west terminals, and it is interesting to note that the geophysical response from the medial bank changes from the classic high resistance to a low resistivity as the eastern terminals are approached, reaching similarly low values to those recorded in the enclosure interior. The appearance of the terminals is discussed further below. Whilst not conclusive, the plots do indicate subtle changes in the resistive and magnetic qualities of the interior of the enclosure. There are three main areas of potential interest indicated in the interpretative plots. The area at the top of each plot is clearly associated with the waterlogged portion of the enclosure, and may have little more significance than that. The two remaining anomalous responses however, may be indicative of disturbance associated with human activity, and again, this is discussed below. The relict field boundaries that were still extant on Plate 5.1 appear on both full area plots. The photographic record indicates that the field boundaries were intact up until at least 1993.

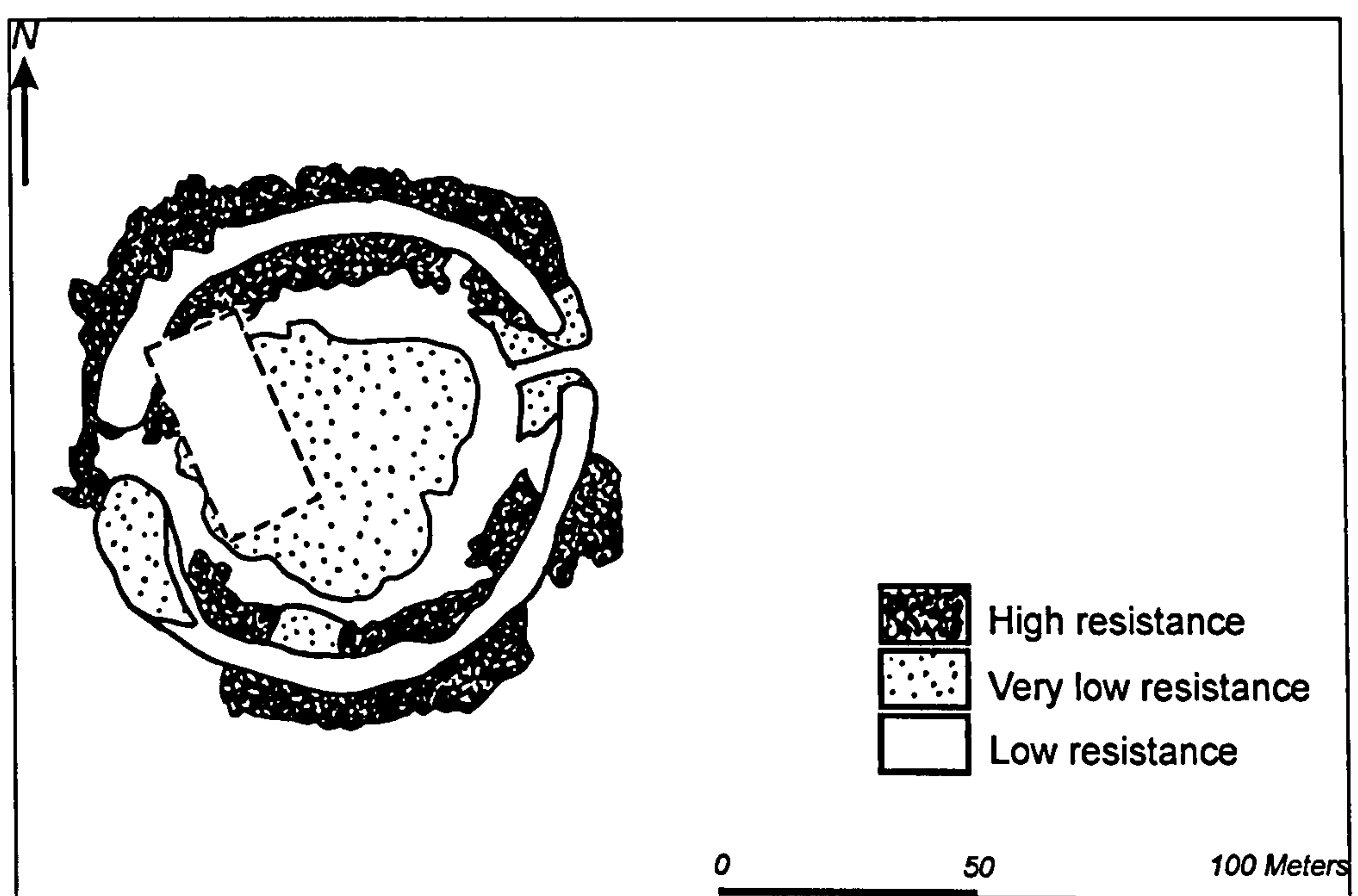


Figure 5.6:

An interpretation of the Resistivity data shown in Figure 5.3 above.

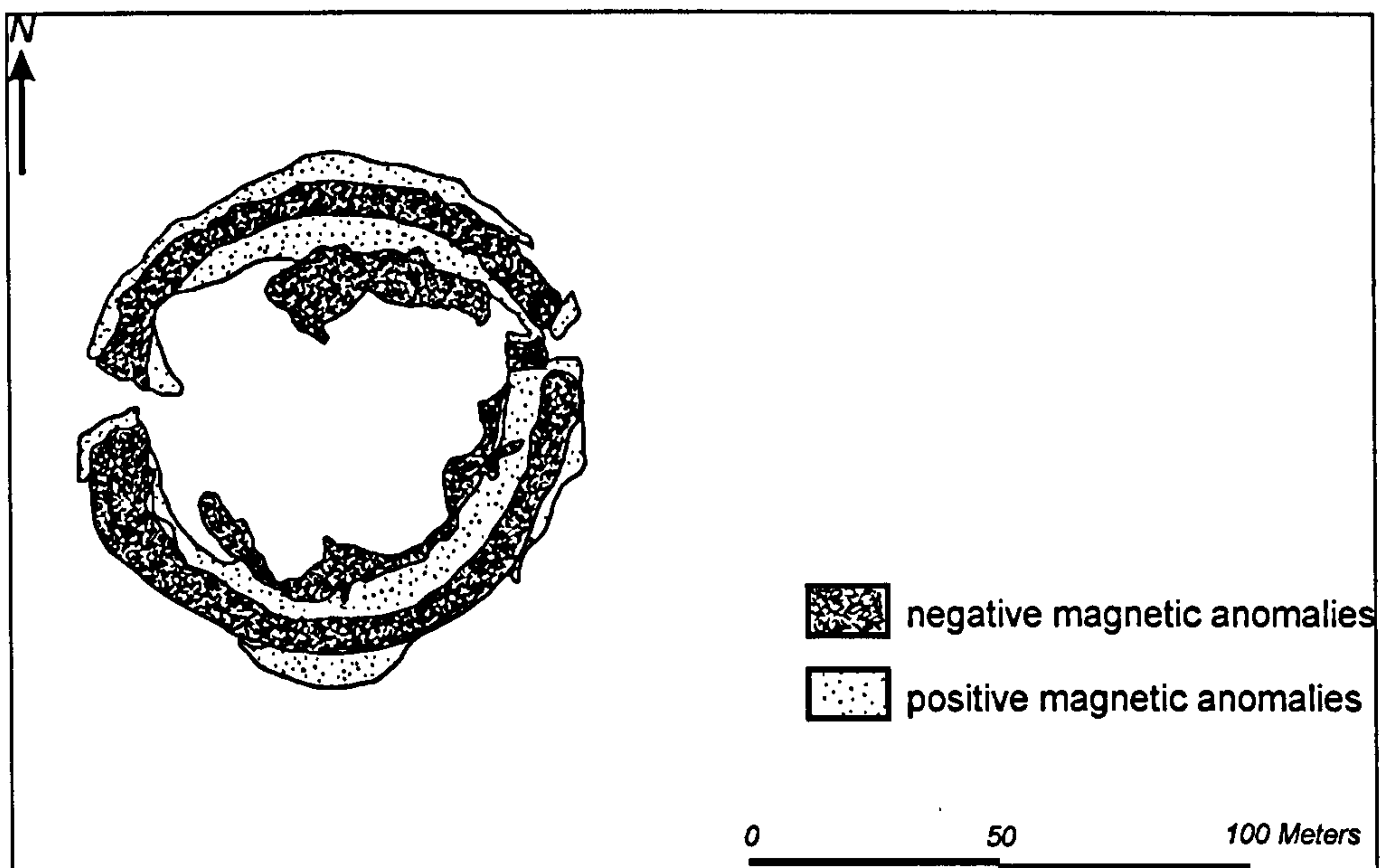


Figure 5.7:

An interpretation of the magnetic data shown in Figures 5.4 and 5.5 above.

A Comparison of Responses From Aerial Photography and Geophysical Survey

By adding the transcribed plan and geophysical plots to the GIS as layers, it was possible to accurately relate the responses from each of the techniques to each other spatially. The outputs from the GIS were then inked up for improved presentation, and are presented in the interpretative figures for all of the case study data in this chapter. In Table 5.4 below, a summary of the information from this source is presented for all three Case Studies. Here, the features that comprise the site (Figure 5.2) are discussed individually.

The Outer Bank

The aerial evidence for the outer bank is complete for the north side, but is only clearly visible around the terminals in the southern arc of the enclosure. It appears as a negative crop mark which is generally very subtle. The magnetic data reveals what at first appears to be only a trace of the outer bank in the north. The narrow rim of positive readings could be interpreted as a return anomaly associated with the negative anomaly derived from the outer ditch. However, comparison with the transcribed plot of the aerial photograph indicates that the anomaly corresponds very closely to the width of the bank mapped from the aerial photographs. A trace of the northern bank, absent from the aerial information, also appears

around its western terminal. The resistivity data reveals increased resistance readings over the area of the bank, but the very irregular, much more extensive area detected relative to the aerial and magnetic information suggests prolonged redistribution of the bank material by the plough. The higher resistance anomaly associated with the bank at the western terminal however, correlates with the discrete, narrow anomaly produced magnetically, suggesting either less plough-damage in this area, or a different construction to the rest of the bank. Figure 5.3 indicates that the plough spread section is constrained by the former field boundary, and the area that appears less disturbed may be due to the direction in which the original smaller field was ploughed, the formation of a head dyke, avoidance of ploughing in this poorly drained section or some other agricultural factor.

The southern arc of the outer bank is geophysically quiet, with the only evidence of its existence coming from patches of similarly spread high resistance anomalies, suggesting that there is substantially more damage in this side of the enclosure. Dispersal of the plough-redistributed material may have been assisted in the southern half of the enclosure by its location at break of slope down towards Craigie Burn. This may have increased the ease with which the bank material was moved away from its original place, as opposed to redistribution from the northern bank, where the ground is not only topographically higher, but redistribution would be impeded by the additional height of the bank itself.

In summary, the outer bank appears as a subtle negative crop mark, which has an associated patchy higher resistance response than the surrounding field, and a positive magnetic signal, which corresponds to the original position of the bank rather than the spread of bank material. The positive magnetic signal is unusual in that the traditionally expected response from a banked feature would be negative, and that of a ditch positive. At this site all of the features display a reversal of the expected magnetic response. This is discussed further in Chapters 6 and 7.

The Medial Ditch

The outer and most obvious magnetic anomaly (Figure 5.4) corresponds to the medial enclosure ditch. This clearly defined negative anomaly correlates completely around its entire circumference at all but the western terminals with the positive crop mark, confirmed

by excavation to represent the outer ditch. This is also the case for the resistivity data on which the ditch appears as a low resistance feature.

The Medial Bank

Again, the entire medial bank can be seen on aerial photographs as a negative crop mark, which together with the crop mark of the outer ditch are the dominant aerial features of this site. In contrast, the geophysical data, which closely correlate for this feature, reveal a very disturbed feature, particularly in the south of the enclosure. Here the anomalies from both techniques are absent in places, and in other areas extend over the location of the inner ditch based upon the aerial photographs. This high-resistance, negatively magnetic anomaly is again consistent with the plough damage that was evidenced in the outer bank anomaly, and tends to support the suggestion of more intense destruction of features in the south of the enclosure.

The Inner Ditch

The inner ditch is visible on aerial photographs, but does not give the impression of a continuous, regular ditch. Rather it suggests a series of scoops, which could be interpreted as either quarries for the bank material, or even hut circle scoops. Unfortunately, the geophysical data fails to resolve the feature clearly. Although the low resistivity anomaly has a slightly more coherent ditch shape than the generally widespread magnetic noise detected in the interior, neither provides conclusive information on the nature of this internal ditch.

The Interior

The interior of the enclosure is marked on the resistivity data as an area of extremely low resistance, lower even than the internal ditch anomaly. This is certainly a consequence of the very poor drainage in the interior. Magnetically, the interior is similarly unresponsive, although the extensive areas of magnetic noise may be the result of extended human occupation causing an increase in magnetic susceptibility internally. This phenomenon has been identified at other UCVLP sites (see Case Study 2) and has been exploited in the identification of probable hut circles. On aerial photographs the interior has a patchy

appearance, occasionally giving the fleeting appearance features that may represent habitation remains but the evidence is never clear.

The Terminals

Transcribed plans of the site suggest that all of the terminals have approximately similar dimensions, with those on the east side and the southern ditch terminal on the west being quite straight, and the remaining three terminals (one ditch and two bank) having a more rounded form. Although the entrances are mainly defined by the ditch terminals on aerial photographs, the bank terminals have also been detected magnetically.

On the east side, the outer ditch terminals correlate well in the aerial and reversed magnetic data, but there is an additional negative magnetic anomaly that bridges the entrance. The medial bank terminals align with the outer ditch in this and the resistivity data, but again the magnetic data indicates a weakly negative magnetic 'bridge' between the terminals. The inner ditch terminals are only visible on aerial photographs and magnetic data, where in the latter, the area of magnetic noise described in the interior does respect the position of the innermost terminal transcribed from the aerial information.

The western entrance terminals show the most morphological variation. Unfortunately this area was not surveyed geophysically because of the presence of standing water. The extent of the water is indicated on Figures 5.3 and 5.4 by the two grids of dummy readings. This prevents anything being said about the geophysical properties of the inner bank and ditch in the north. Aside from this, the data shows that the southern outer bank terminal appears to wrap around the outer ditch edge, and in the north it is truncated on the magnetic data, as is the outer ditch terminal here. The southern outer ditch terminal is exceptional in its bulbous appearance which appears from the magnetic and aerial information to be due to the bifurcation of the ditch as it approaches the terminal. The two ditch sections, which rejoin at the terminal, enclose an area whose magnetic and crop responses correspond to those appearing over banked features at the site. The reversed nature of the magnetic anomalies, however, suggests that this is in fact a ditch, and the resistivity response indicates a cut feature whose low resistance is suggestive of waterlogging on a similar scale to that measured in the enclosure interior. On the ground this terminal is identifiable by a further area of standing water collected in a topographically depressed area, and supports the

interpretation of the resistivity data. It is interesting that the crop growth responses expected from such a moist, ditched feature are reversed in the aerial information, with cut features usually appearing as areas of positive growth. In Chapter 6 this negative crop response is considered in relation to the water availability experiments, where a similar response was noted in pot-grown waterlogged barley. The reversal of the internal bank resistivity anomalies at the terminals from high to low, which appears to continue around the outer ditch terminals to the outer bank may be evidence of similar features existing at all of the terminals, although missing data from the north-west terminals prevents a full interpretation either way. If looked at in relation to the south west outer ditch terminal, these eastern low-resistance anomalies have a similar size and apart from forming a much straighter line at the entrance, have a similar form too. Perhaps the terminals may have undergone alteration from their original form, although the remotely sensed data can not provide information on the phasing of the alterations.

Interpretation of the Site

From the combined remotely sensed data this site is interpreted as a probable settlement site enclosed by two banks separated by a medial ditch, with a probable second internal ditch present. The internal ditch may not be continuous, and may be a function of quarrying for bank material together with some associated anomalies suggestive of scooped hut floors. Although area excavation will be necessary to confirm the function, increased magnetic susceptibility internally, together with ephemeral crop mark information, suggests occupation at this site rather than a ritual function. If correct, it changes the interpretation to an enclosed settlement, with a postulated Iron Age date (Rod McCullagh Pers comm.). However, at least one other possible henge monument in the UCVLP area (Balwaistie henge, NGR: NT304639; NMRS No: NT03NW 63; See Hanson and Sharpe in prep) may have experienced later use as a settlement, and it is possible that this is also the case for Craigie, which may explain the alteration of the terminals.

In terms of the thesis this site provides an example of correlating information from geophysical and aerial reconnaissance data, but with a twist. Whilst the crop mark and resistivity responses conform to those expected for ditched and banked features, the magnetic data shows a reversal of that expected. Instead of the expected positive anomalies over the ditches and negative ones for the banks the reverse is recorded. Despite this all

three datasets record the presence of the main features comprising the site, confirming that they are all affected in a similar way by the subsurface changes. In Chapter 6 the soil chemical environment is examined, and it is hoped that the explanation for this correlation, and for the reversed magnetic anomalies, can be found there.

5.3 Case Study 2: Burnfoot Farm Enclosures

Introduction

A series of enclosures photographed as crop marks in a field at Burnfoot Farm, Libberton (NGR: NS 991405), and introduced in Chapter 4, represent the second of the three Case Studies (Figure 4.1). The site lies in a field to the north of and adjacent to the present farm. The field itself is large, measuring *c* 275 m east - west by *c* 330 m north - south at its widest points. Some of the crop marks recorded are at least in part due to changes in topography, which was described in Chapter 4 (see Plate 4.8). As with Case Study 1, the Burnfoot enclosures lay partially on Upper ORS sedimentary geology, but there is a faulted contact running approximately ENE- WSW through the southern half of the field, bringing Lower ORS age andesites and basalts to the surface. It is interesting to note that this change from sedimentary to igneous geology is not apparent in the geophysical data collected across the site (Figures 5.11 and 5.12), adding weight to the argument that solid geology does not necessarily have a major influence on the quality of geophysical data.

The drift geology overlying these units comprises boulder clay derived from the Southern Uplands, the parent material for sandy clay subsoil cover at the site, which is itself underlain by free-draining brown forest soils, changing to alluvial soils towards the River Clyde. Although the underlying solid geology is different, the drift and soil cover are the same as at Case study 1. As both sites produced coherent geophysical results, this again suggests that the two latter are a more important factor than the former for successful results in all three remote sensing techniques. Because the field is in agricultural use all year round, non-invasive survey was carried out. It was surveyed over almost its entire length using magnetic and resistivity techniques (Chapter 3) and soil samples were taken from a small area of the field (20 m x 60 m; Figure 5.8).

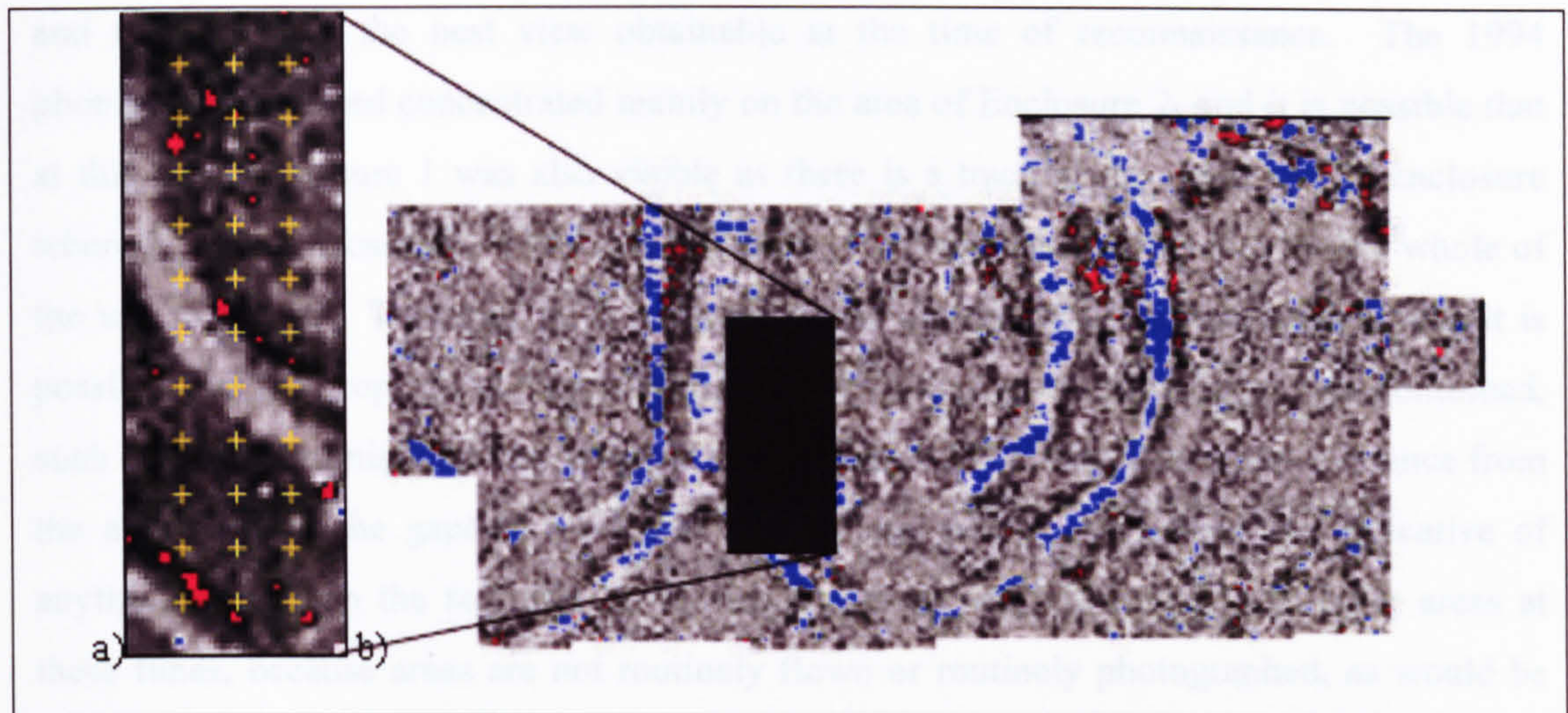


Figure 5.8:

Case study 2 positions of (a) the augur samples relative to (b) the full site survey, indicated for the magnetic data. Red shades represent high resistance/ positive magnetic signals, blue shades represent low resistance/ negative magnetic signals in all plots.

Aerial Photography

Prof Bill Hanson and RCAHMS fliers have photographed the site over a number of years. The NMRS holds a series of aerial photographs of the enclosures (NS94SE 32), which also include a number of CUCAP photographs, some not dated, but Table 5.2 details the information on the available photography. The crop markings reveal a series of six enclosures, and a possible seventh one that is occasionally visible (Plate 5.2). The geophysical survey data suggest that six enclosures are present in the field, and two of these were only noticed on the aerial photographs after the geophysical data had been consulted (Hanson and Sharpe 2001). Figure 5.9 is an interpretative sketch of the site, with the enclosures numbered for ease of discussion.

Site visibility, as would be expected, was not constant for each year for which there is an aerial photographic archive. Table 5.2 sets out the variations in visibility of the enclosures. This indicates that Enclosure 2 is the most reliable of all the features for crop mark formation. In 1989, when Enclosure 1 was not visible from the air, the crop had been sown in an east-west direction over the area of the enclosure and this, together with the direction from which the photograph was taken, may help to explain why (Plate 5.2). However, the assumption is that optimum conditions for crop mark development had not been reached,

and that this was the best view obtainable at the time of reconnaissance. The 1994 photograph examined concentrated mainly on the area of Enclosure 2, and it is possible that at this time Enclosure 1 was also visible as there is a trace of the shape of the enclosure where it joins Enclosure 2. 1989 and 1992 were the least favourable years for the whole of the site to appear. This may be a consequence of the timing of reconnaissance, and it is possible that the crop marks may have developed further as the growing season continued, such is the opportunistic nature of aerial reconnaissance. Neither is there any evidence from the archives that the gaps in the years that the site was photographed are indicative of anything more than the fact that aerial reconnaissance was concentrated in other areas at these times, because areas are not routinely flown or routinely photographed, as would be the case for example with a vertical sortie.

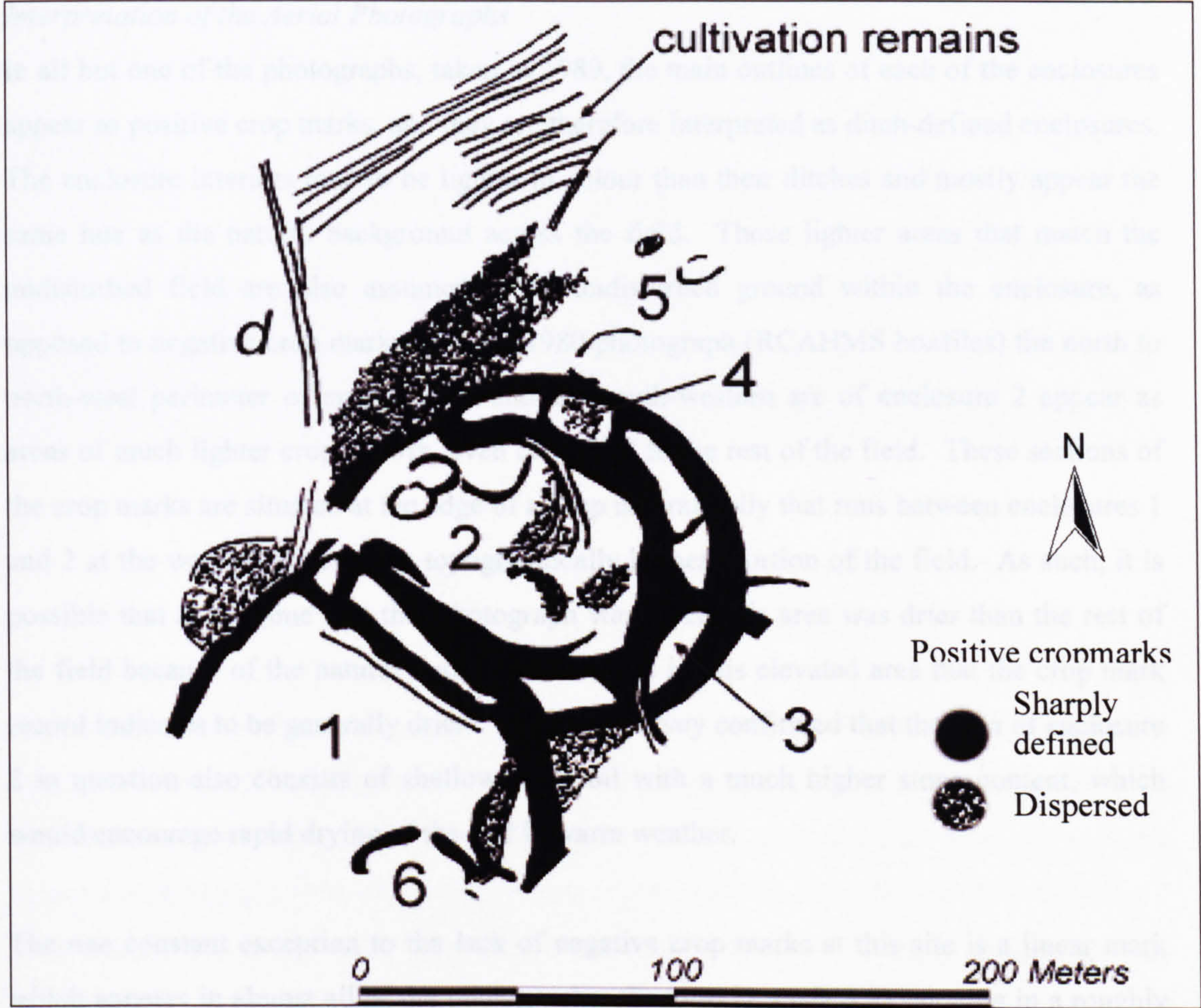


Figure 5.9:
Interpretative plot of Case Study 2 showing the numbers assigned to the enclosures.

Table 5.2: Reconnaissance results at Case Study 2

Date	Source	Taken From	Enclosure						Other Marks
			1	2	3	4	5	6	
Unknown	CUCAP	N	Y	Y	Y	Y	N	Y	Y
Unknown	CUCAP	W	Y	Y	Y	Y	N	Y	Y
1980	CUCAP	SW	Y	Y	N	N	N	N	Y
1980	CUCAP	W	Y	Y	N	N	N	N	Y
1980	RCAHMS	E	Y	Y	Y	Y	Y	N	Y
1986	RCAHMS	S	Y	Y	Y	Y	N	Y	Y
1989	RCAHMS	N	N	Y	N	N	N	N	N
1992	RCAHMS	SW	N	Y	Y	N	N	N	Y
1994	RCAHMS	N	~N	Y	N	~Y	~Y	N	N
1995	RCAHMS	S	Y	Y	Y	Y	N	Y	Y
Geophysics	UCVLP	NA	Y	Y	Y	Y	Y	Y	~Y

Interpretation of the Aerial Photographs

In all but one of the photographs, taken in 1989, the main outlines of each of the enclosures appear as positive crop marks, and they are therefore interpreted as ditch-defined enclosures. The enclosure interiors tend to be lighter in colour than their ditches and mostly appear the same hue as the natural background across the field. Those lighter areas that match the undisturbed field are also assumed to be undisturbed ground within the enclosure, as opposed to negative crop marks. On the 1980 photograph (RCAHMS boxfiles) the north to north-west perimeter of enclosure 1, and the south-western arc of enclosure 2 appear as areas of much lighter crop growth, even compared to the rest of the field. These sections of the crop marks are situated at the edge of a deep natural gully that runs between enclosures 1 and 2 at the western edge of the topographically highest portion of the field. As such, it is possible that at the time that this photograph was taken this area was drier than the rest of the field because of the natural drainage conditions in this elevated area that the crop mark record indicates to be generally drier. The auger survey confirmed that the area of enclosure 2 in question also consists of shallower topsoil with a much higher stone content, which would encourage rapid drying of the soil in warm weather.

The one constant exception to the lack of negative crop marks at this site is a linear mark which appears in almost all of the photographs (Feature D, Plate 5.2), running in a roughly north-east – south-west direction in the west of the field. This is interpreted as a land drain, but would traditionally be interpreted as a walled feature or compacted area reducing the available water in the soil locally and thus impeding growth. However, if the interpretation

is correct the soil in the vicinity of the drain is likely to be wetter if it is drawing water from the field, and, as will be seen in Chapter 6, increased soil moisture can also produce growth that would be traditionally interpreted as a negative crop mark developed in response to a soil moisture deficit.



Plate 5.2:

Aerial Photograph of Case Study 2. © Prof Bill Hanson.

The aerial photograph taken in 1989 showing the perimeter ditch of enclosure 2 and little else very clearly appears to be a reversal mark. Here the normally dark outline appears as a negative crop mark, which if seen in isolation would be interpreted as, for example, building remains, suggesting a bank-defined enclosure or a compacted subsurface, rather than the cut feature suggested by the majority of the photography. Again, the timing of the photography is an important, yet rarely considered, factor in the interpretation (as opposed to collection) of these marks. Additionally, interpretation of this site as a series of ditched enclosures (Figure 5.9), even when showing as a negative crop mark, is highly likely, with interpretation based upon morphology and experience. But are we right to make these

assumptions for all sites? Is it important to take an holistic approach to site interpretation, or should we be paying more attention to the type of crop response recorded in order to secure more detailed interpretations of the nature of the remains?

Geophysical Survey

In March 1999 a programme of survey commenced over the Burnfoot enclosures, which was completed in March 2000, using the methodologies described in Chapter 3. Although there is not as much magnetic data, the cover available is very informative. Apart from occasional slight mismatches in grid edges, a consequence of using several instruments for the training survey, the data is of a high quality. It was considered preferable to leave the mismatches visible rather than to over-process the data. A maximum area coverage of 260 m by 200 m for resistivity, and 240 m by 120 m of magnetic data was achieved, giving a total number of grids surveyed of 93 and 58 respectively. Incomplete grids appear in the resistivity data (Figure 5.10) where there was standing water at the entrance to the field in 1999. Gaps in the magnetic data, again at the entrance to the field, were due to a combine harvester being parked there in 2000, which affected the instrument readings for a considerable distance. Data collection was also stopped short of the grid edge all along the east side of the survey grid because the field is bounded by a metal fence which also affected the gradiometer readings.

Results: The Survey Plots

The resistivity survey results are presented in Figure 5.10 as a grey-scale shade plot that has undergone edge matching of certain grids for the reasons stated above, and despiking of the data to remove readings affected by poor electrical contact between the mobile electrodes and the ground, a combination of encountering areas of stony ground and inexperienced surveyors. Finally the plot was interpolated. The magnetic data (Figure 5.11) is also presented as a shade plot. This was despiked and the zero mean grid function applied to remove grid edge effects, and it too was then interpolated.

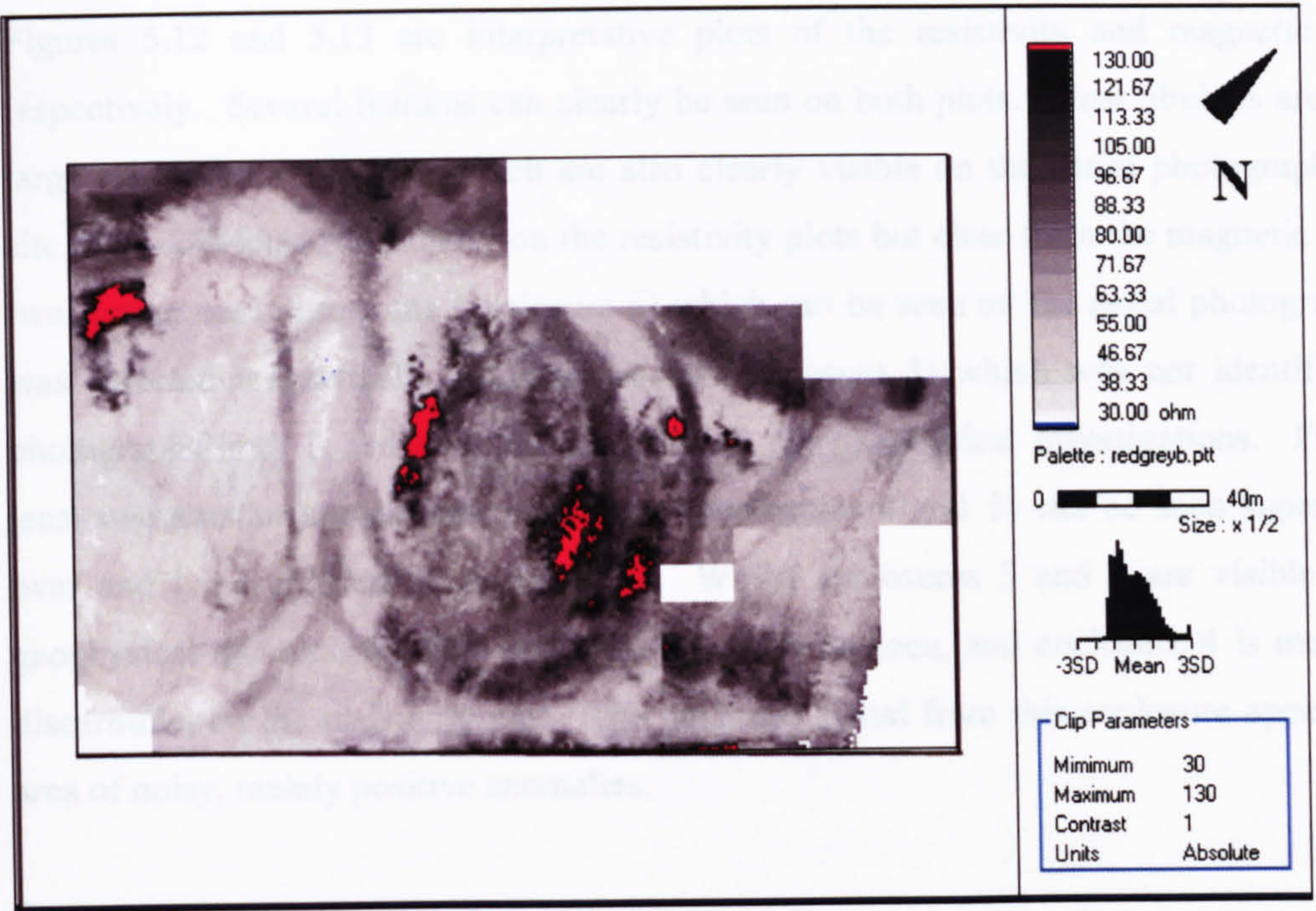


Figure 5.10:
Resistivity plot of Case Study 2.

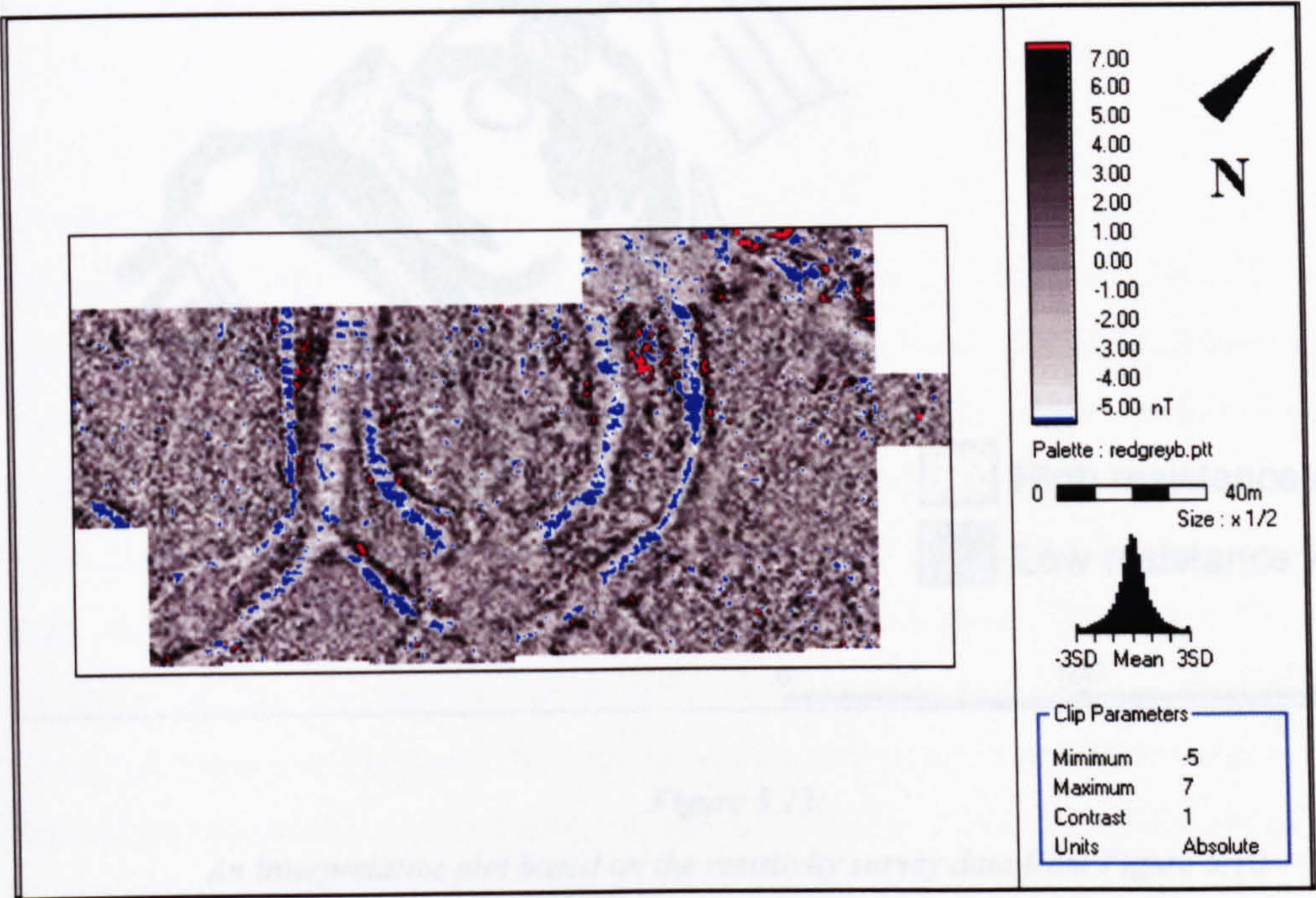


Figure 5.11:
Magnetic data from Case Study 2.

Figures 5.12 and 5.13 are interpretative plots of the resistivity and magnetic surveys respectively. Several features can clearly be seen on both plots. Most obvious are the two large enclosures (1 and 2), which are also clearly visible on the aerial photographs of the site. Less obvious, particularly on the resistivity plots but clear from the magnetic data, are two further enclosures, one (enclosure 6) which can be seen on the aerial photography and was detected magnetically, and the second (enclosure 3) which was not identified from photographs until it had been detected during the geophysical investigations. Finally, at least two smaller sub-circular enclosures (enclosures 4 and 5) can be seen superimposed over and lying adjacent to enclosure 2. Whilst enclosures 3 and 4 are visible on both geophysical datasets, the fifth enclosure can only be seen, and enclosure 4 is more easily discernible, on the resistivity plot. The magnetic signal from this enclosure appears as an area of noisy, mainly positive anomalies.

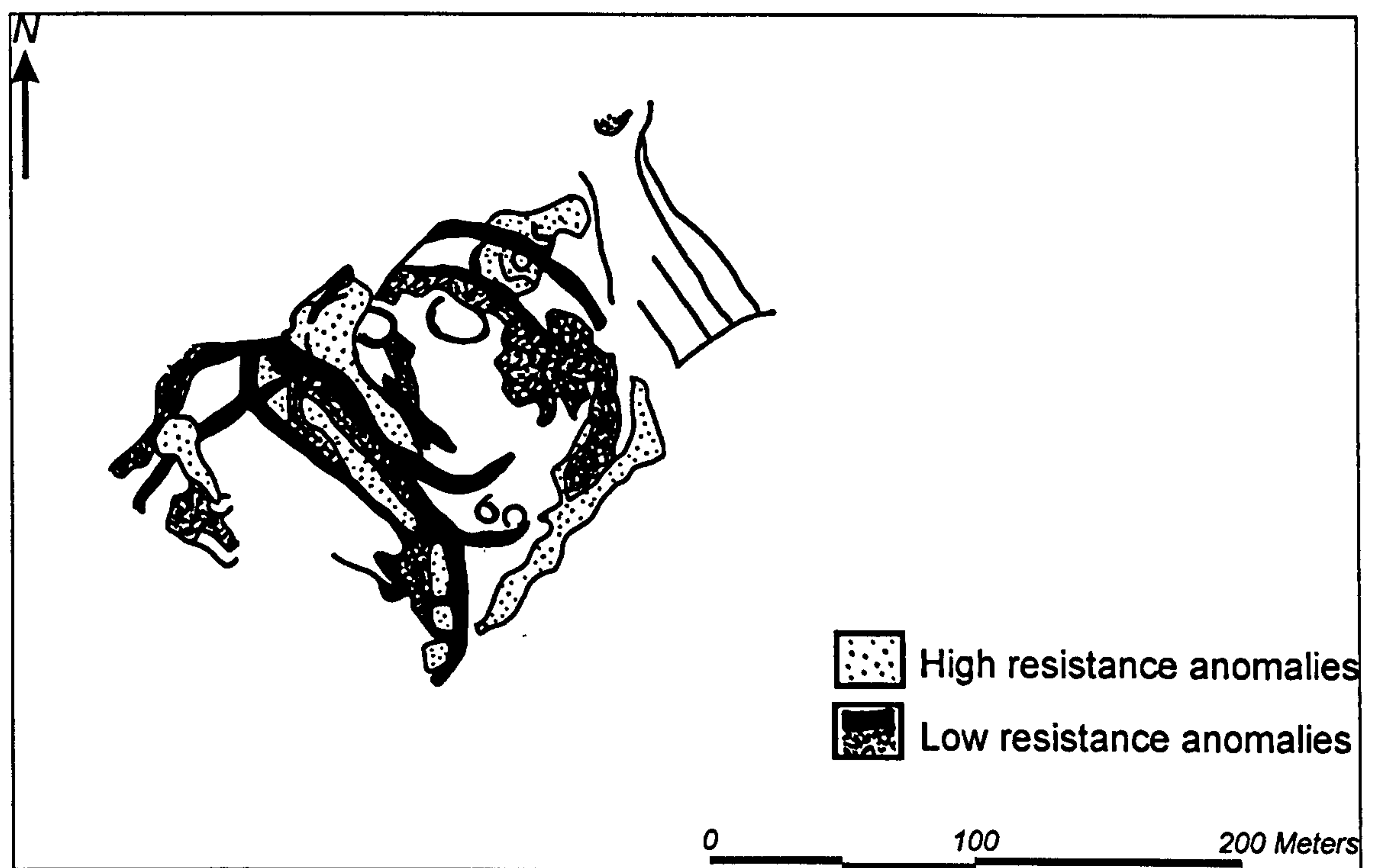


Figure 5.12:

An interpretative plot based on the resistivity survey data from Figure 5.10.

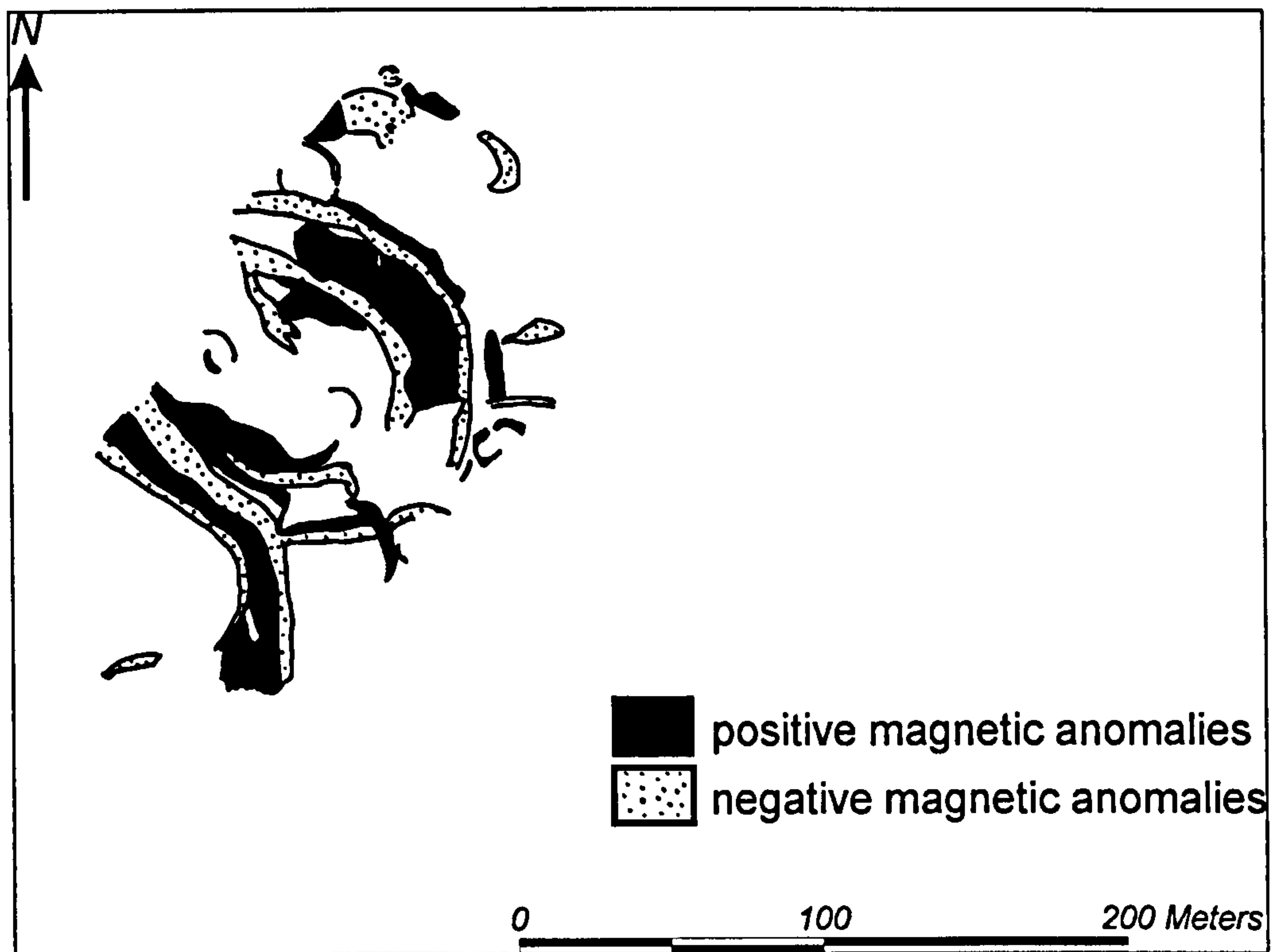


Figure 5.13:

An interpretative plot based on the magnetic survey data presented in Figure 5.11.

Combining the Data

In general, the ditch features that define the enclosures at Burnfoot Farm all appear as positive crop marks on the aerial photographs, and each enclosure is identified with varying ease on the three remotely sensed datasets. There is more correlation between the aerial and magnetic data than there is with it and the resistivity plot. The ditches of the majority of the enclosures all have higher than background resistances, which if taken alone would leave them open to being interpreted as bank-defined enclosures. However, the aerial and magnetic data present responses characteristic of ditches and so they are interpreted as such, given the variety of responses that can be produced by ditches and their weather- and size-dependent resistivities (Clark 1990; Hanson and Sharpe 2001). The information presented here is summarised in Table 5.4 below.

Enclosure 1

Enclosure 1 (see Figure 5.9) produces a positive crop mark above the perimeter ditch, which is not covered in the north-west by the magnetic data. The resistivity data does extend to the edges of enclosures 1 and 2 however. In the north-east the ditch appears as a negative magnetic anomaly of lesser width than the crop mark, which continues round to the east side of the enclosure. The east ditch has a thin negative magnetic anomaly associated with the ditch inner edge. A high-resistance anomaly aligns perfectly with the magnetic ditch anomaly in the north-east, but not on the east side of the enclosure; here the resistivity data suggest a segmented connection between two parallel lengths of ditch, which correlates with the negative magnetic anomaly. The high resistance ditch anomaly actually appears on the combined dataset to be external to the crop mark except in the east of the enclosure. This could be attributed to an error in the transcribed aerial plan due to relief displacement had there not been a correlation between it and the magnetic data, so in this case it suggests that the resistivity high may indicate the presence of bank remains. As with the ditches in enclosure 1 there are discrepancies between the resistivity and aerial photographic responses in the area of the gully. There may be associated with relief displacement in the rectified plan locally, or may be attributable to changing drainage conditions where the topography changes significantly at the break of slope. Internally in this area is an additional positive crop mark suggesting a possible seventh enclosure, which has an associated positive magnetic anomaly.

The area between enclosures 1 and 2, across the large natural gully, produces no crop mark, but is represented by a positive anomaly in the magnetic data. The outline of the two enclosure edges is very confused in this area, requiring excavation to establish the order in which the numerous ditches were constructed and to which enclosure each belongs (but see Hanson and Sharpe 2001). Up to four ditches appearing as positive crop marks flanking or crossing the gully may indicate re-cutting of original ditch features.

Enclosure 2

Enclosure 2 has an almost entire perimeter ditch, marked by a positive crop mark, and associated discontinuous magnetic anomaly. The magnetic anomaly recorded over this outer ditch is positive along the outer edge of the ditch with an associated adjacent inner negative signal, both running around the northern to the southern arc of the enclosure. The high

resistance anomaly from this feature correlates with the positive magnetic anomaly in the north-east, and with the negative anomaly in the south-west, and continues to the southern edge of enclosure 3. The inner ditch, also producing a positive crop mark, has a negative magnetic anomaly in the south-west, which changes to positive in the north-east. The area of positive magnetism corresponds to what appears to be an internal branch of the inner ditch which more closely defines what appears to be an entrance. This magnetic anomaly is associated with the low resistance 'spread' visible in the enclosure interior, which is more extensive on the resistance data than in the other two datasets. The main part of the inner ditch is represented by an area of low resistance which forms an almost complete circuit around the interior.

Between the enclosing ditches in the north-east to the east section, the crop mark has a segmented appearance that produces an associated positive magnetism corresponding with the areas of positive crop growth. In the north-east the high resistance inner ditch is mirrored by the associated positive magnetic anomaly, with both broadening out as they approach enclosure 3 in a similar but more extensive way as the crop mark does. Both responses stop at the point where the ditch of enclosure 3 crosses enclosure 2's ditches, and this interruption of enclosure 2's outer ditches also affects the inner ditch.

A number of responses have been recorded in each of the datasets in the interior of enclosure 2. However, none of the anomalous features correlates in all three of the data sources, making any interpretation based upon these anomalies less secure than it would be had all three responses corroborated each other. There are a number of negative magnetic anomalies flanking the inner ditches in the south-west and north-east with associated high resistance response bordering the northern-eastern and south-western arcs of the interior. The increased resistance may be due to natural outcrops or areas of weathered or plough shattered bedrock, as they correspond to natural topographic highs in the field. Auguring in this area indicated that there was a higher concentration of stone present. A third possibility is that this anomalous area is associated with destroyed enclosure banks. If the banks were constructed of stone, the high resistance anomalies, closely associated with the positions of the perimeter features as they are, may represent rubble spreads due to collapse and plough spreading, with the anomalies spread in the direction of ploughing as indicated by cultivation remains. An extant site located across the river (NS 969 366) can be seen to have a stone-constructed bank similar to that suggested by the geophysical results (Plate

5.3). Additionally, there are positive crop marks, high resistance and negative magnetic anomalies that have forms suggestive of structures such as hut-circles, but there is no correlation between the locations of these internally.

Enclosure 3

Enclosure 3 appears in the aerial photographic record as an arc of ditch in the S, running towards the modern field boundary from enclosure 2. The crop mark developed above the ditch is unusual in that it appears as half positive and half negative cropmark along its length, and has a loosely associated positive magnetic anomaly. In the northern arc of this enclosure however, the crop and magnetic responses are different, appearing as a positive crop mark and a negative magnetic anomaly. The interior and remaining plan of the semi-circular enclosure is defined by a positive crop mark and a lower resistance area which approximates to the shape of the enclosure, resulting in an almost complete break in the perimeter ditches of enclosure 2 in this area which allows the shape of enclosure 3 to be determined. Internally two magnetic anomalies, one positive and the other negative, suggest that the enclosure is a settlement, with these anomalies representing traces of former dwellings. No sign of a continuation of this enclosure into the adjacent field has been noted on the available aerial photography, and geophysical investigations have been limited to the field under discussion.

Enclosure 4

Enclosure 4, which lies between the two ditches in the northern arc of enclosure 2, is defined mainly by resistivity responses with a correlating positive crop mark, indicating a ditch-defined enclosure. The interior contains patches of positive growth, and is marked on the magnetic data by a general increase in magnetic noise. Although not an obvious indicator generally, this has been found to be a characteristic response to the positions of dwellings at UCVLP sites (Hanson and Sharpe in prep). From the resistivity data the enclosure appears as a sub-circular structure, which measures around 25 m east - west. Internal resistive changes, most notably a very high resistance feature in the north-eastern section of the interior, correspond with high positive magnetic responses present.

Enclosure 5

Although there is no direct correlation between responses, the area around enclosure 5 is marked on the magnetic plot by a number of anomalies of varying intensity and polarity, and a similar number of positive crop marks. Some examples of each anomaly type have the approximate form of a hut-circle. The enclosure itself is visible on the resistivity plot, is sub-circular with a maximum diameter of around 20 m, and is defined by a narrow high-resistance outline. Its resistive response is very similar to that of Enclosure 4.

Enclosure 6

Enclosure 6 appears very clearly as a positive crop mark with an entrance in the northern arc, indicating a single-ditched construction that appears from beneath the adjacent modern farm cottage. It is not visible on the resistivity plot and this is assumed to be because the area in which it lies was waterlogged at the time of the survey. A negative magnetic anomaly follows the line of the north-western arc of the enclosure ditch, although the magnetic response is displaced to the north-west relative to the crop mark. This may be due to a displacement of the transcribed plan of the crop mark due to relief displacement as the enclosure lies on sloping ground at the southern corner of the field. Alternatively it may indicate the position of an outer ditch not visible aurally.

Interpretation of the Site

The remotely sensed data reveal a site that comprises six enclosures. Enclosures 1 and 2 are separated on the ground by a deep gully, which is natural, but may well have been exploited during the construction of the enclosures. The survey results suggest this to be so, with definite edges to the enclosure perimeters in this area. Enclosure 2 appears to have been defined by two ditches with geophysically detectable traces of what may have been an associated enclosure bank. It is difficult to infer anything about the relationship of these two enclosures from the geophysical data, but their large size and form suggests they form part of a settlement, with Enclosure 2 particularly forming an enclosed area for a number of dwellings. Enclosures 4 and 5 are examples of such dwellings, which respect the banks of Enclosure 2 and so can be assumed to be either contemporaneous with or later than it. There is little more evidence for this function than their size and position, and the way that they respond geophysically, however. Enclosure 3 appears to consist of one or two ditches

enclosing further hut-circles and, because of the way it interrupts its ditches, is assumed to be of a later date than Enclosure 2. The rectified plan from aerial photographs (Figure 5.9) shows an area of cultivation to the north of the enclosure complex, comprising narrow rig. The area is constrained in the west by what appears to be a field boundary that appears to adjoin the northern edge of enclosure 1. A further trace of a boundary at the east side of the cultivated area separates it from enclosure 5. The whole site morphology suggests an Iron Age date (Prof Bill Hanson pers comm.), although the composite nature of the site may be indicative of a lengthy and phased occupation.

At this site the majority of the features produce geophysical and crop growth responses that are consistent with the ‘text-book’ cases. Generally reversed anomalies, on this occasion mainly resistivity ones, can almost certainly be explained in terms of altered drainage conditions, most specifically at the edges of the natural gully and above the land drain, as discussed. The main controversy regarding the interpretations lies with the question of whether the reversed anomaly detected in association with the ditches of enclosure 2, particularly in the area of enclosure 3, is a response to the remains of a bank that also surrounded the enclosure. A bank of similar construction to that postulated can be seen in Plate 5.3. In Chapter 6 the geochemical responses to this and other features detected remotely at enclosure 2 are examined in the hope of shedding light on the interpretation of the anomalies, and also of further understanding the wider causes of geophysical and crop mark responses to similar buried remains.



Plate 5.3:

Stone constructed bank remains at Park Knowe, Upper Clyde Valley. © RCAHMS.

5.4 Case Study 3: Chesterhall Parks Enclosures

Introduction

Chesterhall Parks Farm is the most southerly of the three sites, as described in Chapter 4. Tenant farmers, Mr and Mrs McCulloch, live in a modern bungalow adjacent to the main A73 road between Edinburgh and Ayr. The house lies around 600 m north-east of the large farm of Chesterhall. Here, the underlying solid geology comprises Lower ORS sedimentary rocks, again with a drift cover of boulder clay, and although the soils are mapped as also being freely draining brown forest soils, similar to those found at Case Studies 1 and 2, the site is in fact covered with a heavy clay soil. As the following section will show, this site produces very different geophysical responses to the preceding Case Studies, and this must be due to some factor associated with the geological or pedological setting, or to the agricultural regimes in place at each of the sites. This is considered further in Section 5.5 and Chapter 6.

Particularly because the railway is embanked quite steeply in the area adjacent to the enclosures, it is difficult to imagine how the terrain appeared originally. One assumes that from the enclosures, the land sloped gently down onto the adjoining flood plain of the Clyde, with the small burn, now culverted under the railway line, running past the western extent of the enclosures. The close proximity to the railway does not preclude the possibility that this settlement was originally more extensive, and has been partly destroyed during railroad construction.

As indicated in Chapter 4, this site was subject to the most extensive of the trial excavations undertaken as part of the UCVLP. This is in part due to the unresponsive nature of the geophysical survey results gathered, which prevented any further interpretation of the site than that elicited from the aerial photographs, which Table 5.3 indicates are sparse.

Aerial Photography

The archive of aerial photographs held, and solely photographed by the RCAHMS is very limited compared to those held for the Burnfoot and Craigie enclosures (Table 5.3 compared to Tables 5.1 and 5.2). This is less likely to be a result of limited flying locally, but rather the limited development of the crop marks. Poor crop mark appearance is likely to be due to

the nature of the soil properties and associated land-use at the site. Conversation with both the tenant and landowner during the 2000 fieldwork season, together with evidence from the excavations reveals the soil in the field to be very heavy clay topsoil combined with a thick clay subsoil layer. The area is kept in permanent pasture because experience shows that the less the soil is ploughed the better quality is the grass crop. This is in direct contrast to the situation at Craigie and Burnfoot, where the soils are capable of mixed arable production. The land is also very wet, with much drainage work having been undertaken, and excavation trenches regularly filling with up to a metre of water after overnight rain. These conditions are certainly not conducive to the development of detectable contrasts either in growing crops or in geophysical data. In Chapter 6, the soil chemistry is investigated to determine whether this also factors into the poor responses to remote sensing techniques.

Table 5.3: Reconnaissance Results for Chesterhall Parks Enclosures between 1977 and 1989

<i>Year</i>	<i>Source</i>	<i>Taken From</i>	<i>Enclosures Visible</i>	<i>Visibility</i>
1977	RCAHMS	NW	6	Poor
1978	RCAHMS	NE	6	Poor
1989	RCAHMS	NW	9	Good
1989	RCAHMS	SE	~9	Good
1989	RCAHMS	SW	7	Good

Interpretation of the Aerial Photographs

Interpretation of the available photography is complicated by the large number of enclosures present at the site, and the irregular way in which each of these produce crop marks. Although the transcriptions of the photographs have proved invaluable in this respect, as has the use of GIS to consolidate all of the data from the aerial photographs and other methods of investigation described here, an additional technical problem arose during transcription of aerial photographs of the site. As Plate 5.4 shows, there are very few control points available around the site. Consequently this, together with the changing topographic height over the field has resulted in sometimes quite substantial displacement errors in the transcribed plans of the site. For this reason it was necessary to manually overlay the plans from magnetic, resistivity and aerial photographic information (Figure 5.14), as combination

of the datasets in ArcView produced a rather confusing muddle of lines rather than the clearly related features revealed at the preceding Case Studies.

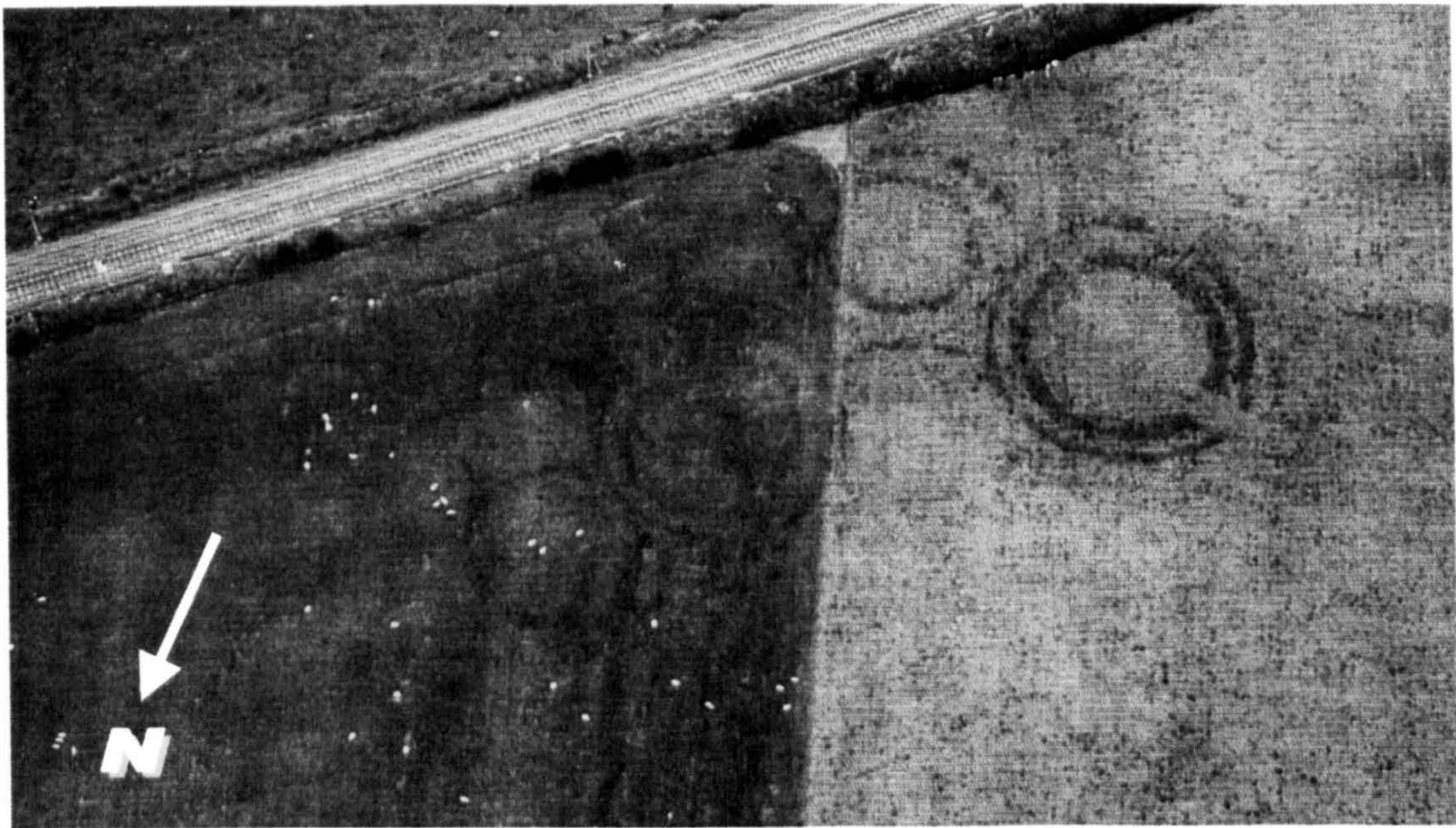


Plate 5.4:
Aerial photograph of Case Study 3.

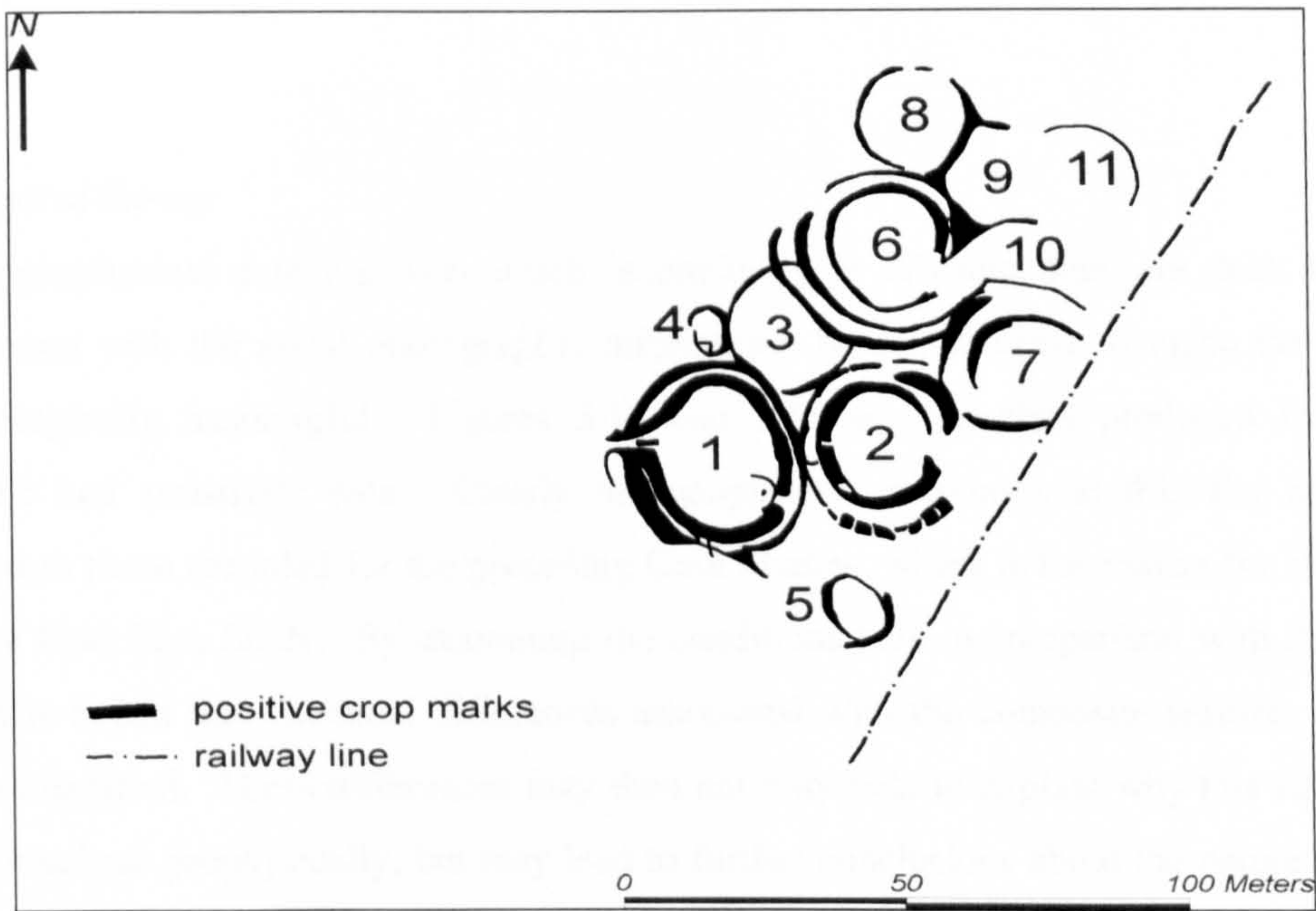


Figure 5.14:
Rectified plan taken from aerial photographs of the enclosures showing the numbers assigned to them.

To ease interpretation, the large double ditched enclosure at the south-western limit of the site was used as a reference point to which all of the other enclosures were related. From this it could be seen that six enclosures are regularly visible on the aerial photographs to greater or lesser degrees of clarity, with a further four or five possible enclosures indicated by subtle and intermittent appearance of altered crop growth. These are depicted on Figure 5.14. From the reference enclosure, the remaining five lie to the north, north-east and south, with the less frequently occurring crop marks indicating up to five further enclosures at the extreme north-east of the site.

All of the enclosures are identified on the aerial photographs by areas of darker vegetation that define their perimeters. These are interpreted and confirmed by excavation as ditches. There are no signs of internal features in any of the enclosures except for enclosure 1, but the site is interpreted as an unenclosed settlement probably dating to the late Bronze Age or Iron Age. Again, excavation has tended to confirm this, despite, or perhaps because of the lack of datable artefacts (Hanson and Sharpe in prep). However, on the aerial photographic evidence alone, all that can be said about this site is that it is a series of up to nine circular and sub-circular, single and multi-ditched enclosures whose age and function are unknown. Unfortunately, the geophysical survey data did little to add to the information about the site, as will be discussed.

Geophysical Survey

As the geophysical data was very much inconclusive at this site, they are dealt with in conjunction with the aerial photographic information below, in order to make the results archaeologically meaningful. Figures 5.15 and 5.16 are the plots produced from the magnetic and resistivity data. Clearly the geophysical responses at this site are very different to those recorded for the preceding Case Studies, which is the reason for choosing it as the final Case Study. By examining the conditions here in comparison with the other sites, it is hoped that chemical differences associated with the composite features at each will be identified. These differences may then not only help to explain why this site could not be resolved geophysically, but may lead to further conclusions about the nature of crop and geophysical responses at sites generally. First, we consider the combined responses of enclosures 1 to 5, for which there is both aerial and geophysical data.

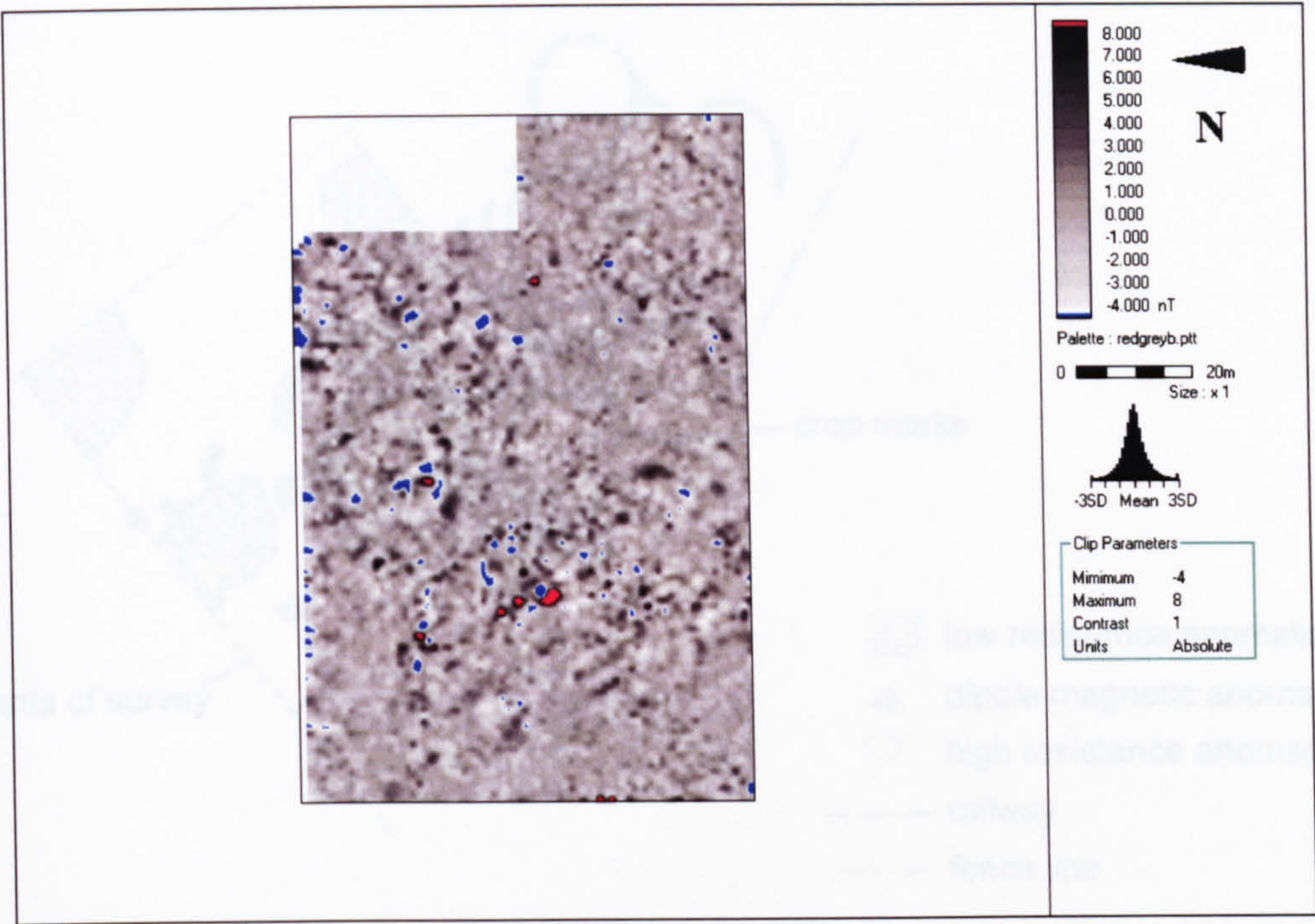


Figure 5.15:
Magnetic data Case Study 3.

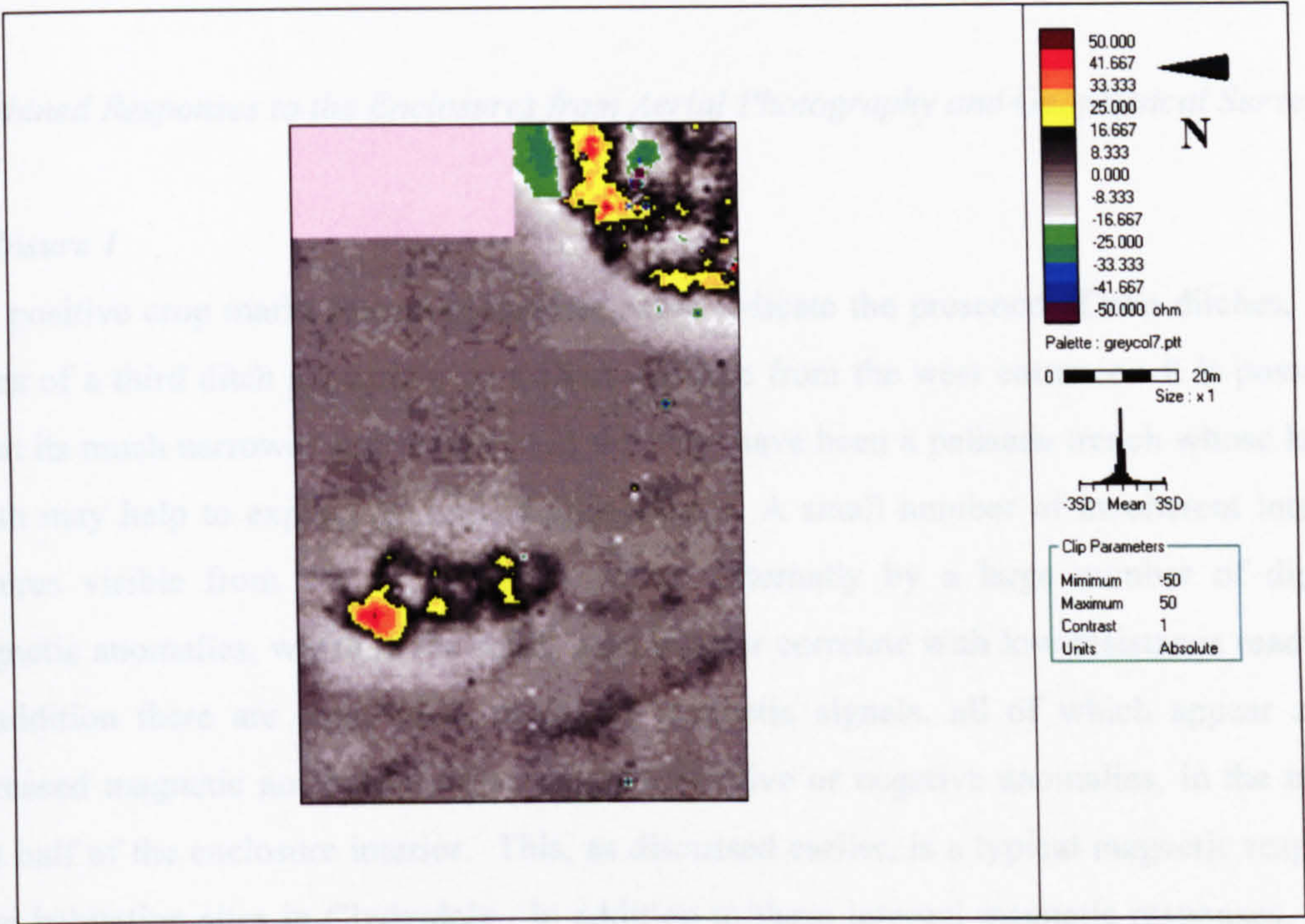


Figure 5.16:
Resistivity data from Case Study 3.

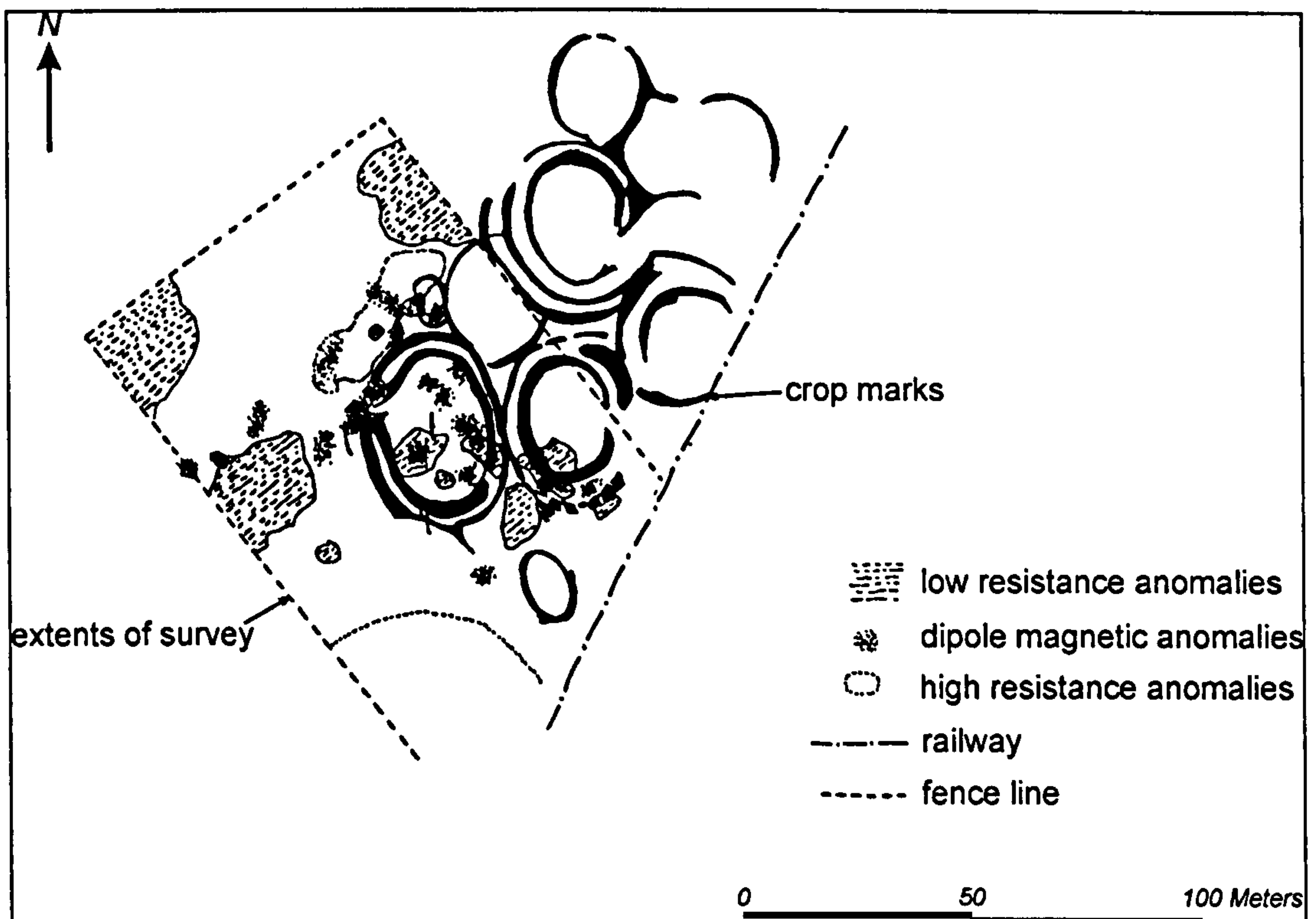


Figure 5.17:
A final interpretation of the remotely sensed data.

Combined Responses to the Enclosures from Aerial Photography and Geophysical Survey

Enclosure 1

The positive crop marks revealing this enclosure indicate the presence of two ditches, plus traces of a third ditch appearing for a short distance from the west entrance. It is possible, given its much narrower appearance, that this may have been a palisade trench whose lesser width may help to explain its limited appearance. A small number of incoherent internal features visible from the air are accompanied internally by a large number of dipolar magnetic anomalies, which in the south-west interior correlate with low-resistance readings. In addition there are some more dispersed magnetic signals, all of which appear as an increased magnetic noise rather than discrete positive or negative anomalies, in the north-east half of the enclosure interior. This, as discussed earlier, is a typical magnetic response from habitation sites in Clydesdale. In addition to these internal magnetic responses, there are a cluster of discrete dipoles recorded at the entrance to the enclosure and defining the area between the ditches on the north side of the west entrance (Figures 5.15 and 5.17). A

possible second entrance appears opposite the west one, although this appears to have been present only in the internal ditch. The aerial evidence suggests that this potential entrance may have been blocked by a structure, with the break in the internal ditch being an original construction which was later blocked up and a second enclosing ditch added. There is an associated low resistance area recorded here, which terminates at the outer ditch, adding weight to this suggestion. This series of low resistance anomalies continues along the southern half of the interior.

Enclosure 2

This enclosure, again defined by the formation of positive crop marks above the two ditches forming its perimeter, is devoid of internal crop marks. The outer ditch appears much narrower in width than the internal ditch, except in the south where it widens out to similar proportions and has a very segmented appearance. Two large patches of low resistance are recorded to the west, and a further, smaller low-resistance anomaly lies at the eastern extent of this segmented part of the outer ditch. There appears to be a single entrance in the north. An arc of a further ditch is visible to the north-east side of this entrance, but does not appear to correspond to either of the two main ditches. As the enclosure overlaps the ditches of enclosure 7 in this area, it is suggested that the ditch modification in this section is associated with the proximity of enclosure 7, but only excavation would determine this relationship unequivocally. The patch of magnetic noise detected in the interior of Enclosure 1 continues into the western side of Enclosure 2. A number of dipolar anomalies are also seen to coincide with the inter-ditch area in the south of enclosure 2, and have associated low resistance anomalies similar to that seen in enclosure 1, with a further dipolar anomaly and resistivity low situated immediately outside the outer ditch in this area.

Enclosure 3

This enclosure is defined solely by a single ditch, recorded aurally as a positive crop mark.

Enclosure 4

This is the smallest enclosure recorded at the site as a single ditched feature comprising a positive crop mark with associated dipolar magnetic anomaly internally. The excavated

feature that was responsible for these responses comprises a deeply buried circular structure whose function was not obvious, but may be associated with metal working or smelting. There was clear evidence of *in-situ* burning, with some burnt wood remaining in section. A small amount of metallic (lead-based) slag was found in the feature's fill (for a full description of the excavated evidence see Hanson and Sharpe in prep).

Enclosure 5

As with enclosure 3, this feature was revealed by a positive crop mark only, which revealed a small single-ditched enclosure. It has similar dimensions and form to that of enclosure 4, but without associated dipolar responses internally. A magnetic anomaly of similar shape to the adjacent enclosure ditch lies a short distance to the west, which may also represent the enclosure ditch given the anticipated placement error of the transcribed crop mark plan (see above).

Other Responses

On the magnetic data (see Figure 5.15) a few discrete areas of magnetic noise and scatters of dipolar anomalies can be seen in the north-west. Although there are no associated crop marks, the responses may indicate a continuation of the site into this area, which did not have an effect on crop growth at the time of reconnaissance. Again, this could only be confirmed by excavation, although the responses are very similar to those associated with enclosures 1, 2 and 3.

Resistivity highs appear at various places in the plot (Figure 5.16) and are in the main associated with topographic rises, presumed to reflect changes in either underlying geology, drainage conditions, or a combination of both. One exception to this is the high resistance patch appearing at the north-west edge of enclosures 1, 3 and 4. This anomaly respects the outer ditches of these enclosures but this may not be as significant archaeologically as it first appears as the anomaly also marks a change in topography as the ground here rises slightly up to the next terrace on the hillside. It does however suggest a predictable exploitation of the topographic setting in the siting of the enclosures by their builders, and the high resistance effect is likely to have been enhanced by the increased rabbit burrowing activity noted in this area. It is possible that this increased activity is a result of burrowing into

softer substrata, and taken together with a correlation with the magnetic noise, described above, may mark the continuation of the site postulated from the magnetic data.

Trial Excavation of Three Enclosures

Enclosures 1, 2 and 4 were trial trenched during the fieldwork stage of the UCVLP. The soil samples analysed (Chapter 6) are from bulk samples of each context taken during trial excavation of enclosure 2 (Hanson and Sharpe in prep). Although this analysis allows a close examination of several of the features revealed during excavation, in a way this may be less informative than the auger surveys at the previous sites. The reason for this is that the samples do not directly relate to the bulk soil conditions measured during geophysical examination, or to those resulting in differential growth, each of which represent the combined effects of a vertical slice through the individual layers. This is discussed in Chapter 6. A full excavation report is forthcoming (Hanson and Sharpe in prep). A probable Iron Age date for these enclosures has been postulated based on the combination of morphology (Prof Bill Hanson pers comm.), the presence of large amounts of cremated bone comprising the floor layer in Enclosure 2 (J. Roberts pers comm.), and the presence of metal working evidence within enclosure 4, which was excavated to investigate the magnetic responses recorded at its location. Finds made from this trial trench included lead slag and ore, presumed to have come from Leadhills (c.20 km to the south-west; A Hall pers comm.).

5.5 Conclusions

This chapter evaluates the information for each of the Case Studies derived from aerial and geophysical data. The features that each of the sites has in common are ditches that define the enclosure perimeters, with occasional evidence for habitation areas. The latter responses tend to be detected geophysically, rather than be revealed as crop marks, and are identified particularly by the presence of patches of magnetic noise. Excavation at Case Study 3 confirmed that random noise of a dipolar nature marked habitation areas for this site, but further excavation of similar responses at other sites will be necessary before the signal can be firmly described as a characteristic of former dwellings, especially given the exceptional nature of Case Study 3. However, this type of response can theoretically be expected due to

enhanced magnetic susceptibility in confined areas that have seen both repeated lighting of fires and accumulation of organic matter, as would be expected in a prehistoric dwelling.

Each of the Case Studies has its own geophysical question to be answered. At Case study 1 there is a need to understand why the magnetic responses are reversed, while Case Study 3 requires an explanation for the poor geophysical results overall, especially as substantial features have been shown to exist during trial excavations. Case Study 2, while being able to be described as the site conforming most closely to the expected geophysical and aerial responses, has the question of the interpretation of the reversed resistance anomalies, and whether they represent the remains of banks, to be considered.

This chapter allows us to begin to answer some of the questions posed in Chapter 1, although most of the answers must wait for Chapter 7 when all of the remotely sensed and experimental information introduced here and in Chapter 3 can be brought together. Following examination of the remotely sensed data for the Case Studies we can say for definite that at case Studies 1 and 3 the crop marks and geophysical responses occur over mainly cut features remaining from the use of the sites during the Prehistoric period. At the very least the responses are due to a disturbance of the stratigraphic layers and an interruption of soil formation processes during and after occupation of the site. At Case Study 1 no significant changes in soil moisture were detected during limited test pitting, although there were pronounced changes in soil texture, structure and colour that allowed the different contexts comprising the site features to be identified. Similarly at Case study 3 the water content within fills of features was not noticeably different, although the site was significantly more wet and poorly drained than was Case study 1, with water collecting in the excavated ditch of enclosure 2 which was over 1 m deep after a night of heavy rain. This wet heavy clay soil environment is the main factor that can be identified as the cause of the poor geophysical results and limited crop mark formation at this stage of the investigation. Although there was no excavation at Case Study 2 general field conditions and the moisture content of the augured soil samples indicates that Case study 3 is indeed unique in its possession of poorly draining soils.

Table 5.4 summarises the responses recorded for the main features at each of the sites, and forms the basis for the pooling of field-collected and experimental information, presented in Chapter 6, that will allow this work to be brought to a conclusion in Chapter 7. At this stage

the interpretations made from the remotely sensed data have reached their limits, and have been taken as far as is normal. However, to move on and be able to answer the rest of the questions posed at the beginning of this thesis, the possible causes of the remotely sensed responses must now be considered. To be able to understand any links between the aerial and ground-collected information both must first be examined individually and any factors found to be common to data gathered from both platforms can then be investigated to determine whether they are responsible for the correlations between datasets. This is what Chapter 6 attempts, and a discussion of whether this attempt has been successful appears in Chapter 7.

Table 5.4: Summary of the Remotely Sensed Data for the Case Studies

Case Study	Feature	Crop Mark			Resistivity Anomaly			Magnetic Anomaly			Correlation
		Positive	Negative	Average	High	Low	Average	Positive	Negative	Average	
1: Craigie	Outer bank		Y		Y			Y			Magnetic and aerial data
	Outer ditch	Y				Y			Y		
	Inner bank		Y		Y			Y			
	Inner ditch	Y				Y			Y		
	Interior	Y	Y	Y		Y				Y	
2. Burnfoot: Enclosure 2	Outer ditch	Y			Y			Y	(associated)		Magnetic and aerial data
	Ditch reverse anomaly/ bank between ditches		Y		Y				Y slightly		All
	Inner ditch	Y			Y mainly	Y			Y		All
	Interior	Y			Various responses			Y			Mixed
3. Chesterhall Parks: Enclosure 2	Outer ditch	Y				Generally lower over enclosure		Some magnetic noise but no coherent anomalies			None
	Inner ditch	Y									
	Interior			Y							

Chapter 6: Experimental Results

6.1 Introduction

In this chapter I return to the experimental work introduced in Chapter 3, and present and examine the results. An empirical examination of crop growth and information on elemental variations at the case study sites, and in glasshouse-based experimental groups is provided in an attempt to ascertain why certain responses occur in remotely sensed data, and whether they have a common cause. As detailed in Chapter 3, five different experimental groups were set up, which involved growth of spring barley in various media, followed by ICP-MS analysis of various of the soils and some of the plants grown in them, with some subsidiary measurements of properties such as pH, conductivity and magnetic susceptibility being measured for some of the soils and plants. These are presented alongside the main experimental results.

6.2 Experiment 1: The Germination Test

Figure 6.1 shows the number of seeds that germinated from a batch of 100. A 90% viability was recorded for the seed batch based upon this test. Emergence of the plumule (embryonic shoot) as well as the radical (seed root) was required before the seed was counted as having successfully germinated (Plate 6.1).

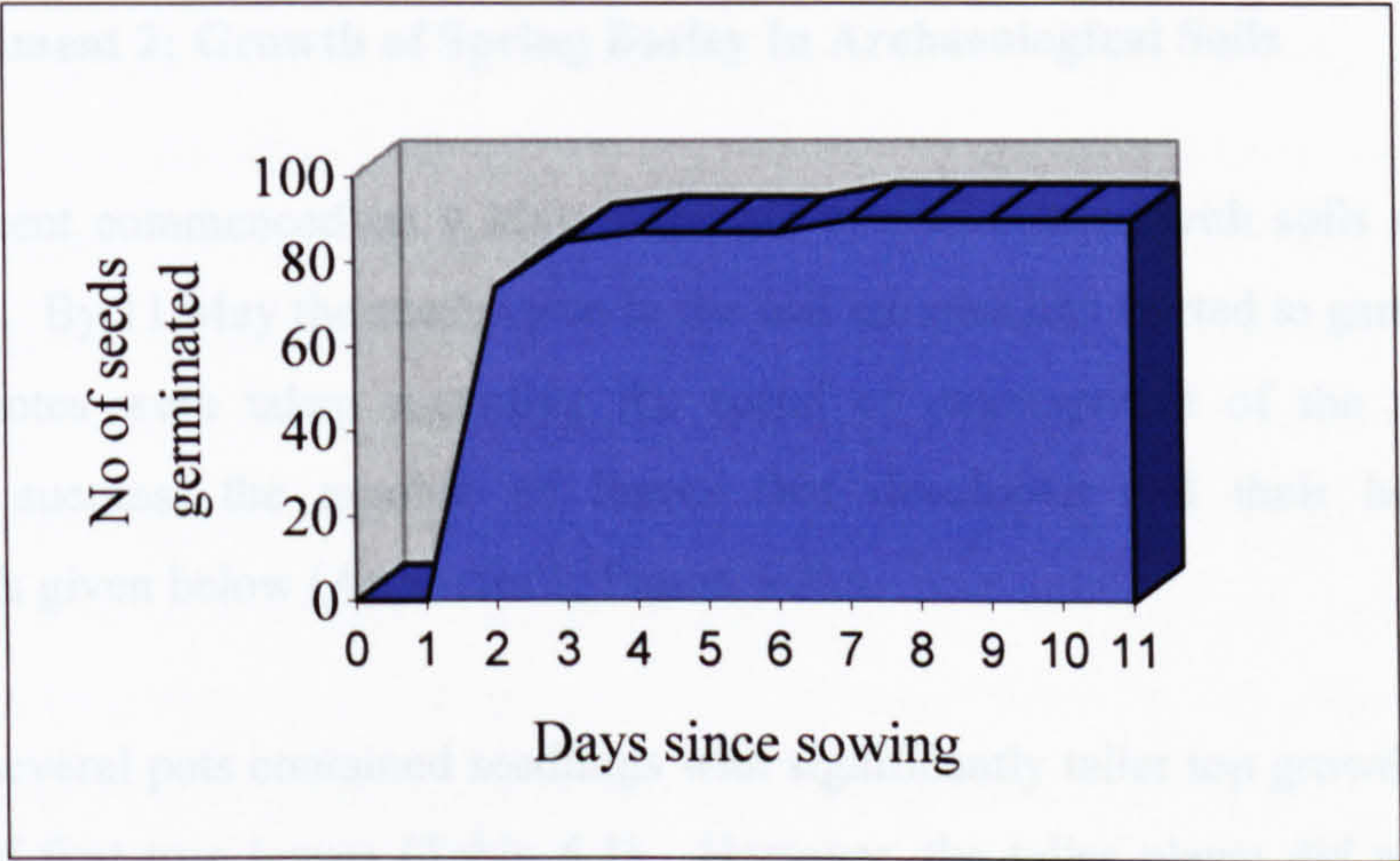


Figure 6.1:
Germination success of the test batch.

Testing the viability of the seed batch in this way allows the effects of differing experimental regimes on germination rates to be assessed, with any significant departure from the 90% germination rate being attributable to environmental conditions rather than to poor seed quality.

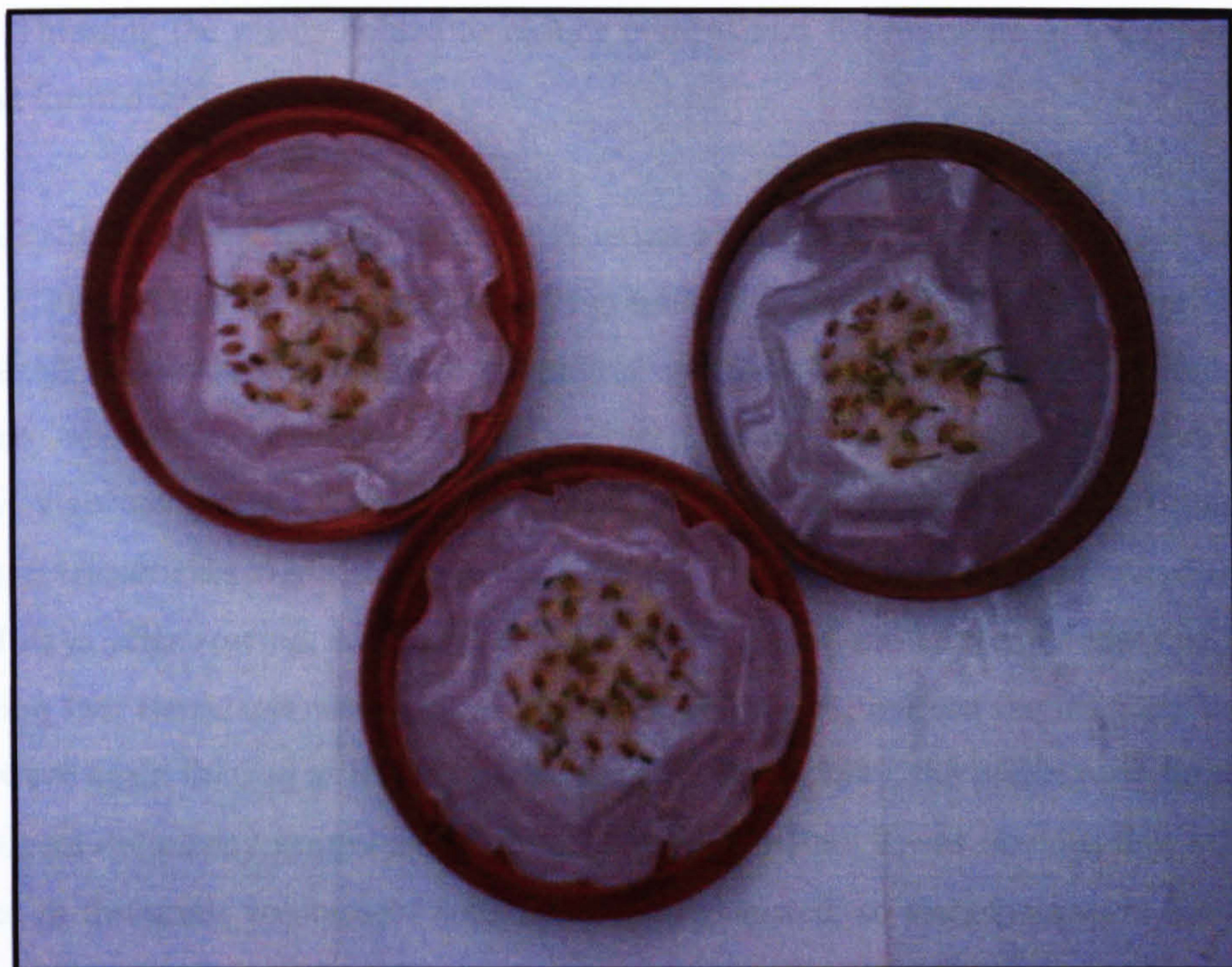


Plate 6.1:

Seedlings germinating on filter paper.

6.3 Experiment 2: Growth of Spring Barley In Archaeological Soils

This experiment commenced on 9 May 2000 and was associated with soils sampled from Case Study 2. By 11 May the seeds sown in the soil samples had started to germinate. From this stage, notes were taken regarding the speed of development of the seedlings, the germination success, the number of leaves that developed and their heights. This information is given below (Appendix 1; Figure 6.2).

By 13 May several pots contained seedlings with significantly taller top growth and a higher proportion of first true leaves (Table 6.1). However, the taller plants did not necessarily correspond to the pots with the highest numbers of germinated seeds. This may represent the development of an effect similar to that seen in favourable years over recently sown cereal

crops, the so-called germination marks (Riley 1996, 27). It was clear following assessment at this stage that the more significant factor affecting visual impact (i.e. greenness) was the differences in the numbers of seeds that had germinated, rather than the advanced development of individual plants. As growth continued, and after recording the numbers of plants per pot and leaf heights (Table 6.1) the seedlings were thinned out to five per pot (15 May). Thinning the plants helped to reduce competition for nutrients in these small plant pots and limited soil volumes.

Plate 6.3 shows what these figures mean in terms of the actual appearance of the plants and Figure 6.2 represents the germination rates graphically. The control information was taken from plants grown in proprietary horticultural compost (Chapter 3, p.96), which provides optimum nutritional, structural and textural conditions, which should therefore produce healthy, vigorous plants. The control plants were omitted from the graphs because their growth characteristics significantly exceeded those grown in archaeological contexts. By 17 May, 9 days after sowing, roots had begun to grow out of the bottom of most of the pots, indicating that the plants were outgrowing their containers, and on the 22 May the young plants were again thinned to leave 3 plants per pot. By 26 May, the plants were beginning to show visual deficiency symptoms (Plate 6.2), and on 5 June it was obvious that all nutrient reserves in the small volumes of soils had been exhausted, so the plants were harvested as described in Chapter 3.

Figure 6.2b represents mean final germination rates for plants grown in soils augured from the individual site features. The outer, and to a lesser extent the inner ditch, and interior appear to have slightly enhanced germination rates, which may be visible aerially if translated into a field situation. This corresponds with the expected crop response, with reports confirming enhanced early growth over ditches where germination marks have been observed (Chapter 2 p59). The anticipated positive crop growth over these features also correlates with this result, with plants that could potentially form positive crop marks having a head start on those surrounding them during the early stages of the growing season. More importantly this suggests that the cause of germination marks is less likely to be a soil moisture effect as in this experiment the watering regime for each pot was standardised. Therefore, factors remaining that are likely to be responsible for this effect include soil temperature and, related to this, soil colour. These are discussed below.

Table 6.1: Growth Effects in Soils Taken From Above Features, as Determined by Aerial Reconnaissance and Geophysical Survey, at Case Study 2

Pot No	Feature Above Which Soil Augured	No of Seeds Germinated	No of Leaves	Average Leaf Heights, cm
1	Inter-ditch	3	10	4.87
2	Internal ditch branch	2	9	2.80
3	Inter-ditch	1	1	0.00
4	Inter-ditch	5	11	2.03
5	Internal ditch	5	4	6.26
6	Outer ditch reverse anomaly	4	10	1.27
7	Internal ditch	5	3	5.44
8	Internal ditch	3	0	0.00
9	Control	7	11	10.17
10	Internal ditch	7	10	5.33
11	Interior	6	8	3.95
12	Inter-ditch	4	5	6.65
13	Interior	7	4	7.40
14	Internal ditch	6	9	5.26
15	Inter-ditch	5	6	9.93
16	Outer ditch reverse anomaly	4	5	5.66
17	Interior	8	6	6.46
18	Interior	4	2	10.05
19	Interior	5	6	9.95
20	Interior	5	6	9.73
21	Interior	10	9	6.23
22	Internal ditch	6	6	9.42
23	Outer ditch	3	2	6.80
24	Outer ditch	5	7	10.70
25	Internal ditch	4	2	10.70
26	Inter-ditch	5	4	4.98
27	Exterior	5	6	7.34
28	Inter-ditch	3	10	7.35
29	Interior	7	10	8.51
30	Inter-ditch	9	3	4.38
31	Exterior	4	10	5.67
32	Inter-ditch	5	8	4.75
33	Internal ditch branch	8	11	5.81
34	Interior	5	5	6.70
35	Interior	8	6	6.15
36	Inter-ditch	5	4	9.70
37	Interior	3	0	0.00
38	Inter-ditch	4	12	4.88
39	Interior	4	2	6.87
40	Inter-ditch	4	9	4.80
41	Interior	4	4	7.23
42	Interior	6	4	5.67
43	Internal ditch	6	6	7.23

In this experiment there was more rapid germination initially in the plants grown in soils taken from the interior and exterior of the enclosure at Case Study 2, with, one day later, similar germination rates being observed for ditch soils. By 17 May germination rates were similar in all of the pots. This illustrates how fleeting a phenomenon germination marks are likely to be. Regular recording of such marks is made less likely still due to the time of year (winter or spring) that barley commonly germinates, compared to the most active time of year for reconnaissance (summer).

A later development likely to be visible aerially occurs in young crops when the number of leaves per plant is established above individual archaeological features (i.e. the crop density). Accordingly the number of leaves per pot was recorded in Experiment 2 (Table 6.1). This indicated that those plants grown in soils from the enclosure interior had higher numbers of leaves, although two days later the seeds sown onto ditch soils developed similar numbers of leaves. Three days later there appeared to be similar numbers of leaves present in all of the Experiment 2 pots.

Quantitative Assessment of Growth Characteristics

As discussed above there were differences in the germination rates of the seedlings with some, for example those in pots 3, 6 and 8 (inter-ditch, interior and again inter-ditch respectively), having no seedlings (Figure 6.2a), or indeed signs of foliage until well in to the growth period. On the 12 May, the soil temperatures, known to be a factor in the speed of germination of seeds (Riley 1979, 30), were recorded in each of the plant pots. As temperature is a function of soil texture and colour, as well as air temperature and prevailing weather conditions, it is likely to be significant to germination success over sites that produce soil marks, and is also likely to contribute to their ability to produce crop marks under these circumstances. Figure 6.3 shows averaged germination rates relative to soil temperature. Soil temperature measurements were made only once due to the limitations of the soil thermometer (see Chapter 3), and are not considered to be wholly reliable. Additionally no obvious trends in temperature were noted that could be related to the soil samples' origins (Figure 6.3).

Despite this inability to correlate soil temperature with seedling development an analysis of the growth characteristics, shows that there are observable growth differences under glasshouse conditions in plants grown in soil overlying archaeological features at Case Study

2. Moreover, these observed differences concord with those expected to be produced during crop mark development for each feature type under field conditions. This affords a measure of confidence in not only the data, but also the experimental design. Perhaps more importantly, as mentioned above, as the watering regime was standardised for all of the pots in this experiment, the results suggest that a source other than differential water availability must be sought for the variations in growth at this site, and perhaps all crop mark sites.

At harvest, growth in the individual pots varied somewhat within feature groups, and no clear patterns of growth relating to numbers of leaves per plant or plant heights was readily discernible from graphical presentations of the data. Nor could the groups of plants grown in soils from individual features be differentiated by their wet or dry weights when harvested. Ultimately there were no obvious differences between the plants grown in soils augured from the individual features as identified from geophysical survey and aerial photographic information. It was very difficult to assess the collected data visually for groups of plants, divided by feature, due to the wide variation in values within groups as the preceding charts (Figure 6.2a for example) have demonstrated. This variation is to be expected between individual living organisms, and in this case large variation about the mean is exacerbated by the small sample sizes of the populations being examined. Visually however, growth differences did remain in the plants, as Plate 6.3 shows. These plates serve to illustrate how attempting to quantify the results of this experiment effectively removes what are obvious visual differences between the plant groups. From this it was clear that merely generating graphs for the per pot data was not necessarily a good way to treat these results.

Whilst taking these variations into consideration, the growth characters were re-examined graphically using the averaged values for each feature, grouped into plants grown in soils from the enclosure interior, ditches, inter-ditch areas and from outside the enclosure. Despite in some cases there only being 1 or 2 pots for some features, this was nevertheless considered to be the best way to deal with the data. The small sample number of replicates for some of the experimental work was a consequence of sampling on a grid basis at a site comprising some narrow and spatially small features, and this limitation of samples is recognised as problematic but unavoidable for some of the features. Figure 5.8 (Chapter 5) indicates the points in the geophysics grid from which each of the samples were taken.

Figures 6.2b to 6.4 present the averaged data for the feature groups. It is clear that this treatment produces a much simplified set of results that are easier to discuss, and this

simplification is considered to be justified for examining the growth characteristics as it effectively reduces them to crop characteristics per unit area, which equates in the field to crop density. In this case as there were approximately 5 plants per 10 cm² (including the space around each 9 cm diameter pot) the crop density equates to around 500 plants per square metre. This compares to field sowing densities of 350 seeds per m⁻² for spring barley, and 400-450 per m⁻² for winter sown crops (Kerr walker, SAC, pers comm.)

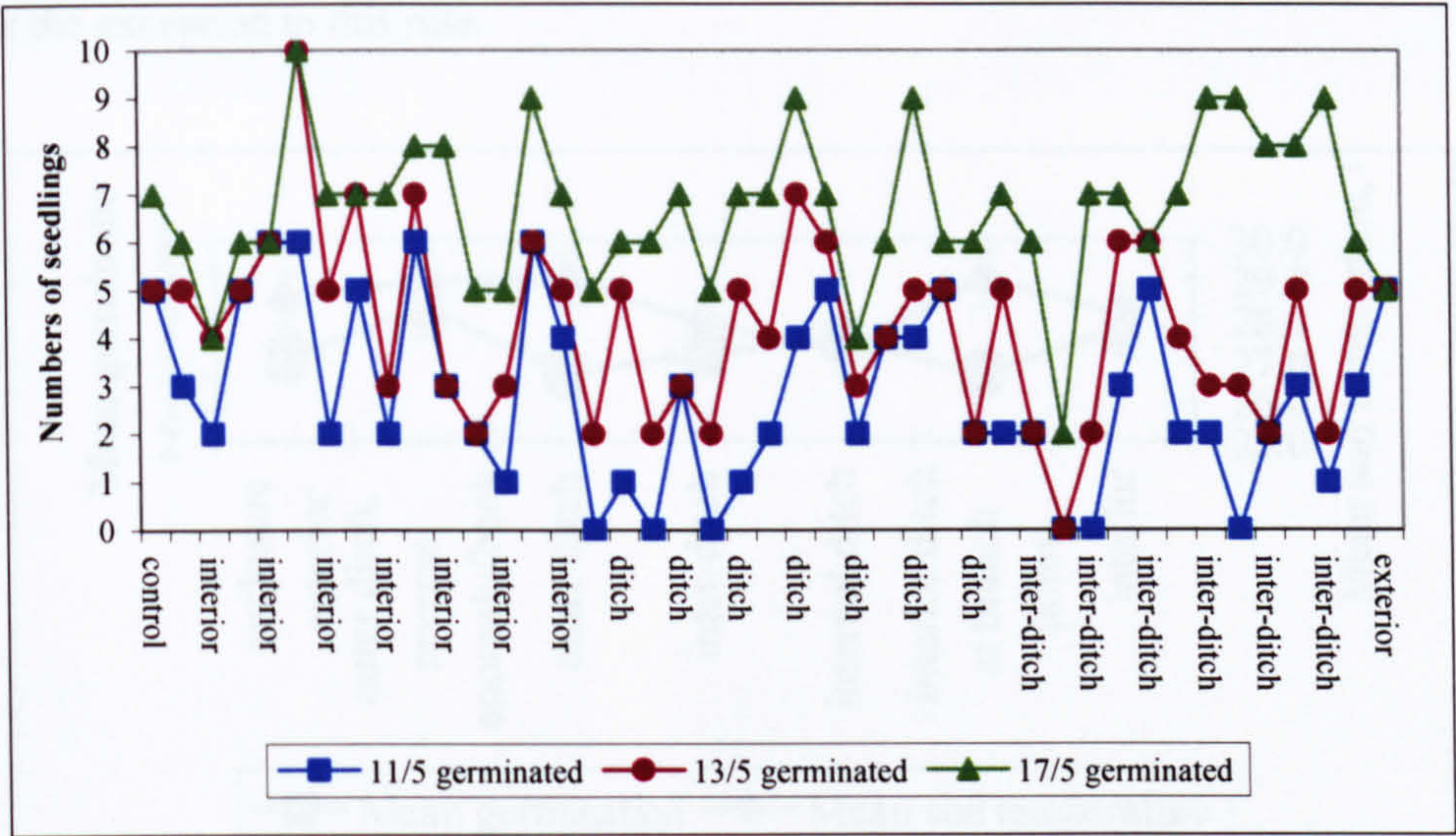


Figure 6.2a:
Weekly germination figures per pot.

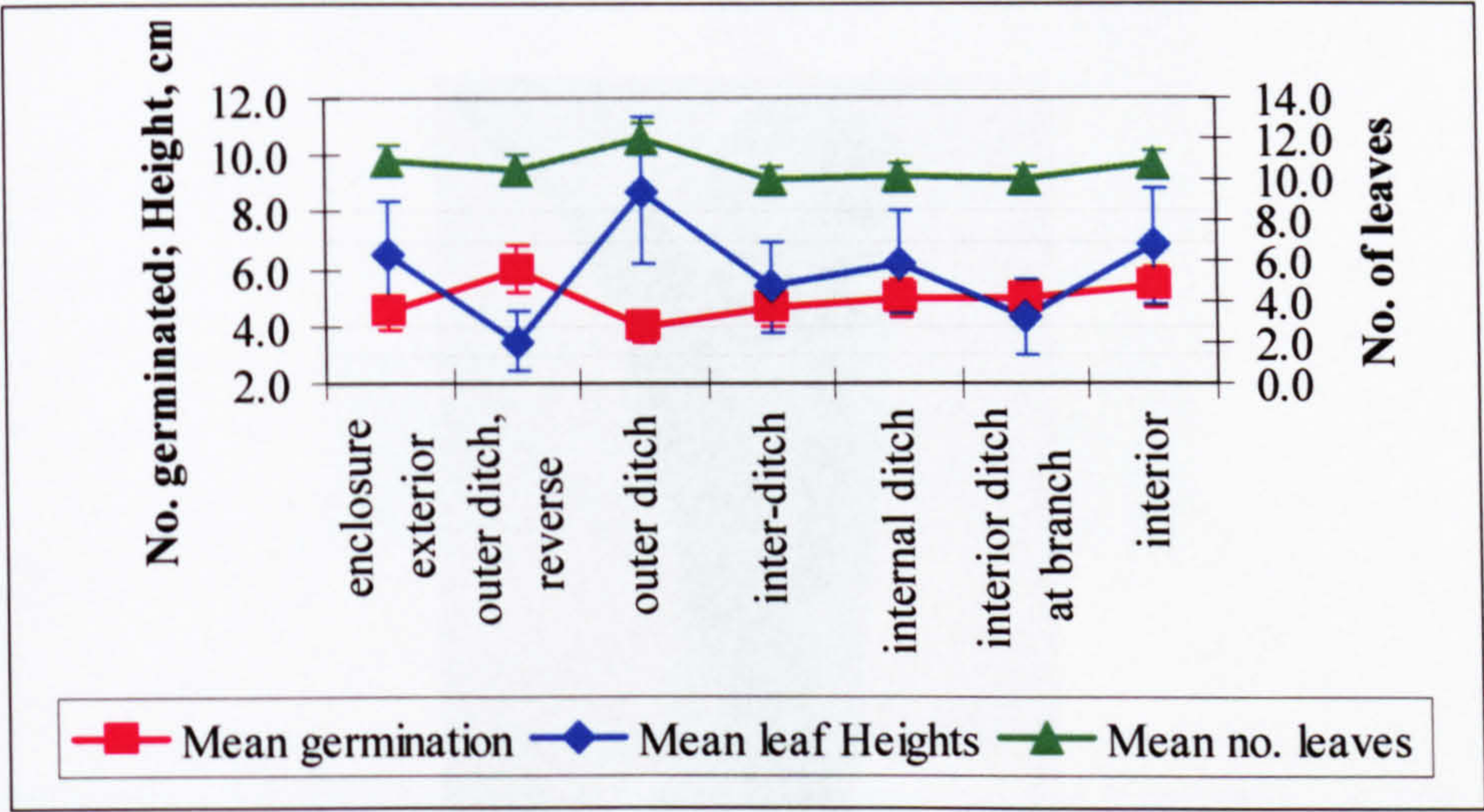


Figure 6.2b:
Mean germination, leaf heights and numbers of leaves, averaged by feature.

In Figure 6.3 the mean germination rates are presented relative to average soil temperatures. Generally within this temperature range seeds are known to respond more favourably to higher temperatures during germination, however this data suggests an inversely proportional relationship between higher soil temperature and better germination rates. For example, inter-ditch and internal ditch soils have relatively high germination but the lowest soil temperatures, while the branch of the internal ditch has one of the lowest germination rates but one of the highest soil temperatures. The reverse anomaly associated with the outer ditch is the exception to this rule.

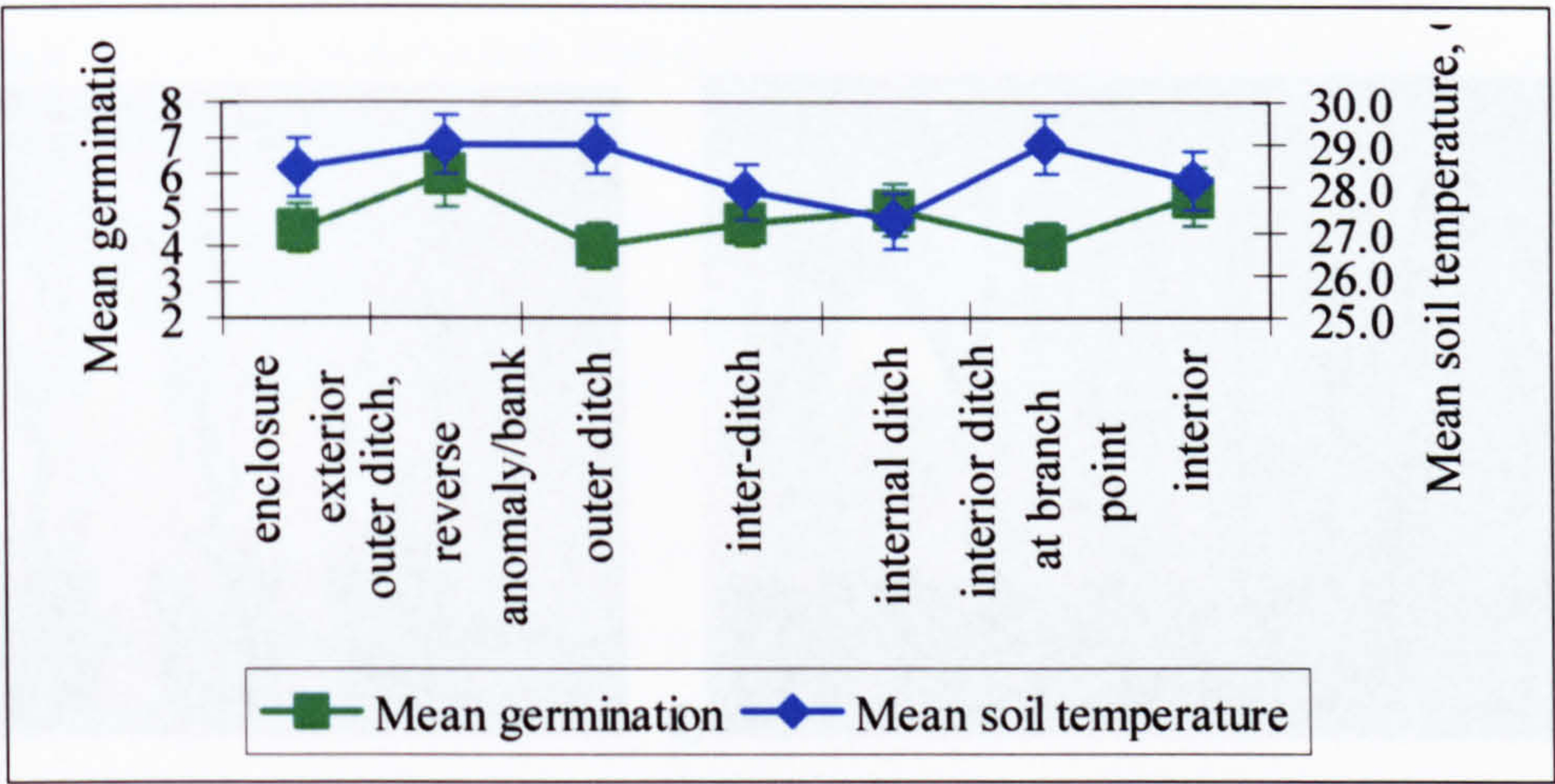


Figure 6.3:
Mean germination for the features lying below auger points at Case Study 2 and soil temperature.



Plate 6.2:
Deficiency symptoms appearing in a plant grown in soil from the enclosure interior.

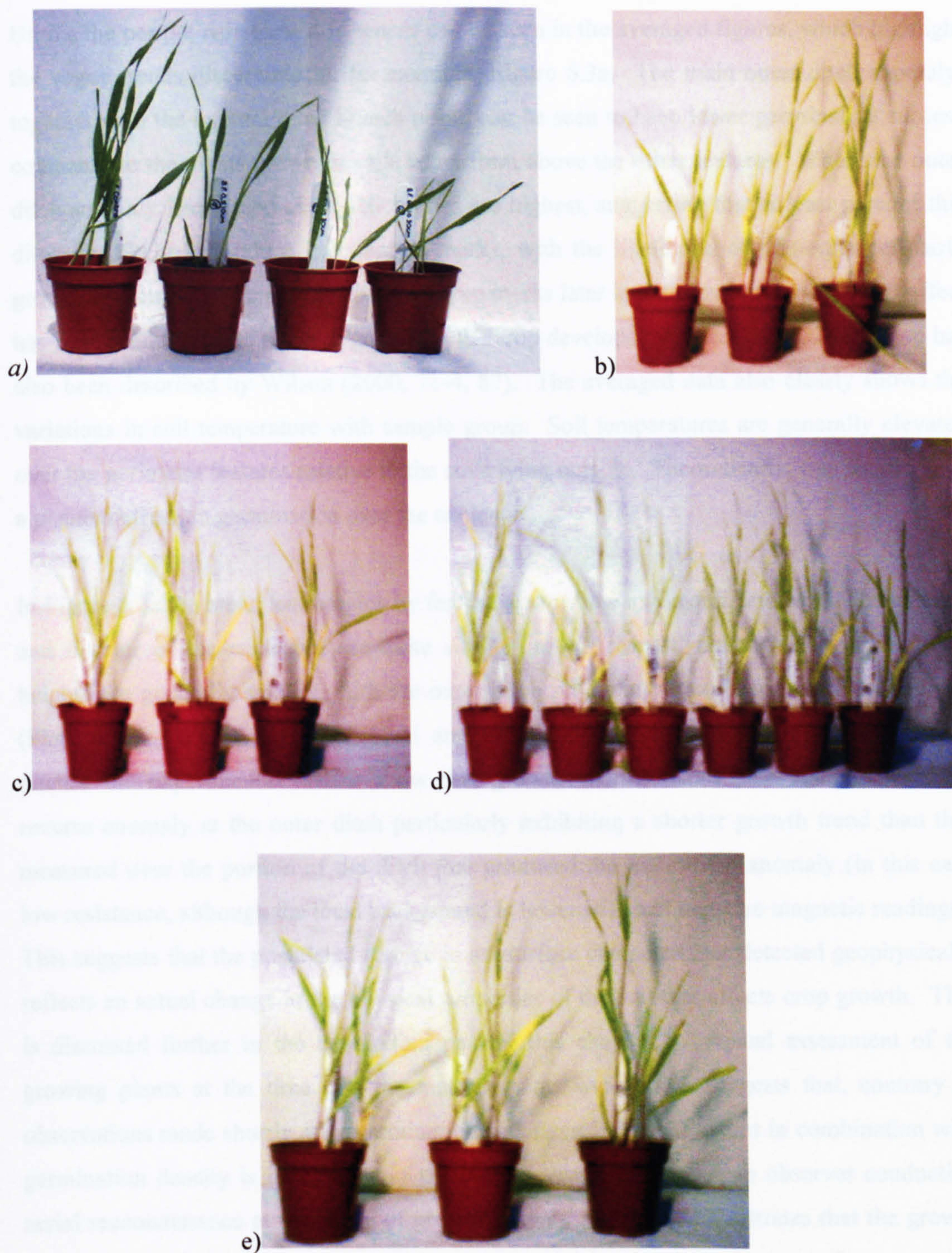


Plate 6.3:

Growth differences in Experiment 2 plants at harvest showing from left to right:
a) General differences during growth; b) Inter-ditch; Internal ditch at branch point; Interior; c) all grown in soils taken from the enclosure interior; d) Inter-ditch; Internal ditch; Internal ditch; Interior; Interior; Interior and e) Interior (negative growth patch in crop mark); Inter-ditch; outer ditch.

Unlike the per pot data clear differences can be seen in the averaged figures, which highlight the vague trends discernible in, for example, Figure 6.3a. The main outer ditch anomaly, together with the internal ditch branch point, can be seen to have lower germination success compared to the plants grown in soils taken from above the other features. Where the outer ditch anomaly is reversed germination rates are highest, suggesting that at least parts of this ditch are likely to produce germination marks, with the likelihood of this enhanced early growth continuing on to produce positive crop marks later in the growing season. This effect has been seen to turn to positive growth as the crop develops by Allen (1984, 75-78) and has also been described by Wilson (2000, 71-4, 87). The averaged data also clearly shows the variations in soil temperature with sample group. Soil temperatures are generally elevated over the perimeter features relative to the soils lying outside. Theoretically, this should have a positive effect on germination over the enclosure.

In Figure 6.3a the mean leaf heights by feature again show marked differences. The exterior and interior of the enclosure are quite similar in this respect, although the internal leaf heights are generally smaller, with the outer ditch producing the tallest growth on average (Plate 6.3e). Where the geophysical anomalies indicate changes in properties for both ditches the experimental results show that growth characteristics also change, with the reverse anomaly at the outer ditch particularly exhibiting a shorter growth trend than that measured over the portion of the ditch that produced the main ditch anomaly (in this case low resistance, although the local background is lower still, and negative magnetic readings). This suggests that the postulated change in subsurface characteristics detected geophysically reflects an actual change in the physical properties of the soil that affects crop growth. This is discussed further in the concluding part of this chapter. A visual assessment of the growing plants at the time that the measurements were made suggests that, contrary to observations made shortly after germination (see page 193), leaf height in combination with germination density is likely to have the biggest visual impact for an observer conducting aerial reconnaissance at this stage of growth. Again, the data demonstrates that the growth trends expected in an archaeological crop mark are initiated at an early stage of crop growth. It is interesting to note that in this dataset the soils taken from the interior and exterior (both devoid of crop mark features as discussed in Chapter 5) have produced growth that is on average the same height, and that the inter-ditch, while not generally considered to be a negative crop mark feature on the basis of the aerial photographic interpretations, has produced growth that could be classified quantitatively as such.

Figure 6.3c indicates the average number of leaves developing in soils from above each feature, and can be seen to follow the same trend as the graph of leaf heights, although the differences are more subdued in this case. The figures reveal that the outer ditch soils again support a larger average number of leaves per pot than the soils taken from the other features. This too supports the idea of positive crop marks being initiated in the early stages of growth. The inter-ditch and internal ditch have the lowest average number of leaves per pot, and for the internal ditch at least this contrasts with the positive growth expected above the ditches in the crop marks (see Chapter 5). Although not a negative mark as discussed above, the less vigorous growth associated with the inter-ditch area has however clearly been established during the early stages of growth.

As described in Chapter 3, the leaf areas were measured for the individual plants grown. This data is presented in Figure 6.3a as averaged by feature. The outer ditch plants have the highest mean leaf area, and the internal ditch the lowest variations between individual plants in each group conform to this trend, as the error bars confirm. The altered or reversed portions of the anomalies recorded at the inner and outer ditches continue to reveal differences in growth characteristics from those above the 'expected' anomalies from the respective ditches. In this case the outer ditch reverse anomaly has a lower, although still relatively large mean leaf area, and the inner ditch branch has an average leaf area larger than the remaining inner ditch plants, of a similar size to that measured for plants grown in inter-ditch soils. Leaf areas for the plants grown in soils from the exterior and interior of the enclosure are again relatively similar.

Finally, the averaged dry weights for the plants grown in soils from individual features are presented in Figure 6.3b. The outer ditch soils produced the greatest amount of plant material, followed by that from soils external to the enclosure. The inter-ditch and internal ditch at the point where it branches into two produced the least amount of plant material. Again, with the possible exception of the latter, this is consistent with that expected from a field assessment of crop mark features, and this is discussed in detail below.

Table 6.2 summarises the growth characteristics recorded for the Experiment 2 plants. It highlights the fact that, despite having the lowest germination rates, plants grown in soils from the outer ditch have the highest numbers of leaves, largest leaf area and the tallest plants on average. This contrasts with plants grown in soils from the area of the ditch that produced a reversed geophysical anomaly (see Chapter 5). In this area soils taken for

Experiment 2 produced the shortest of all the plants, together with those from the inner ditch which developed plants with small numbers of leaves, and the lowest leaf area. The enhanced growth of the outer ditch may be in part due to less competition for resources as a result of the lower germination rates.

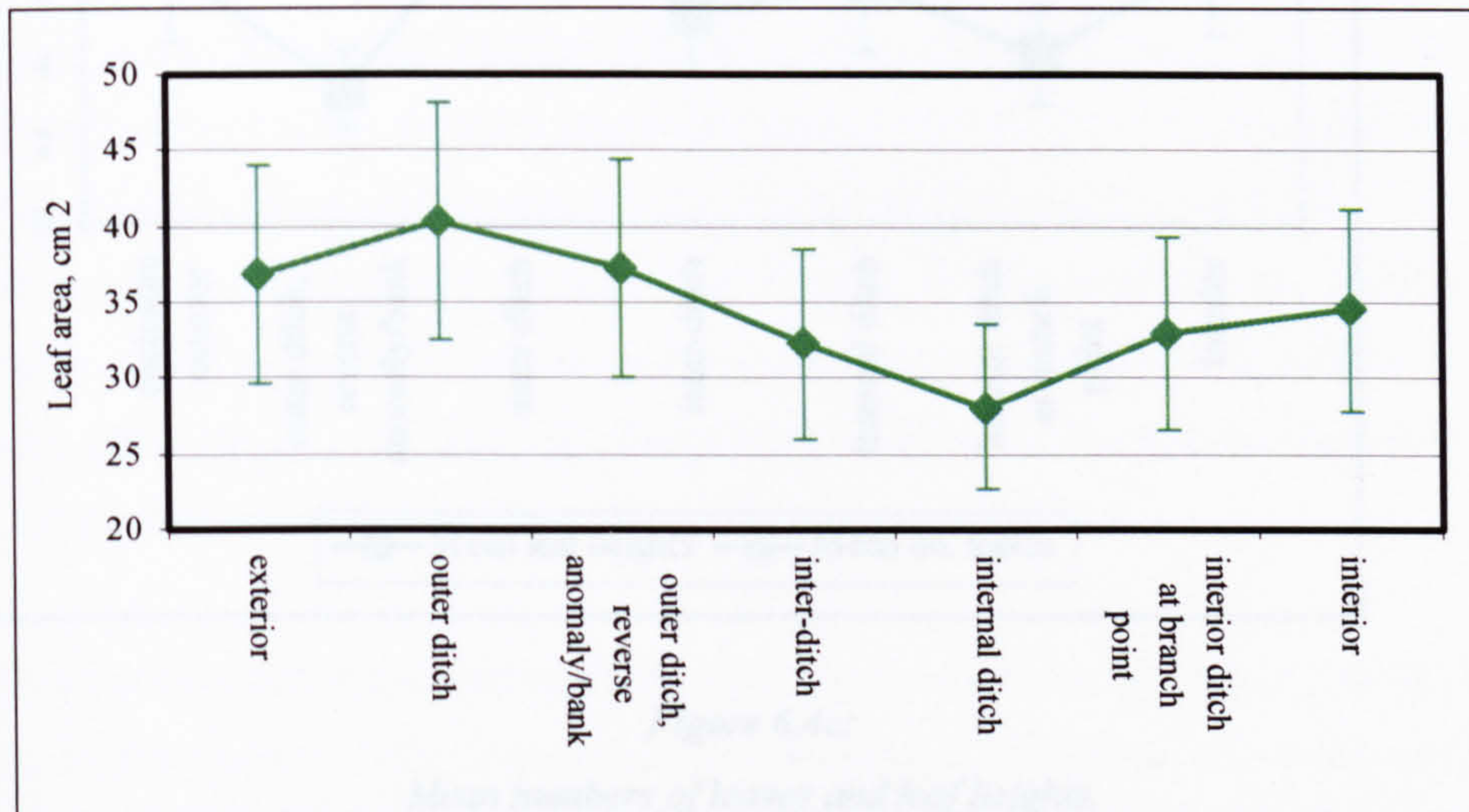


Figure 6.4a:

Mean leaf areas for each feature from Case Study 2.

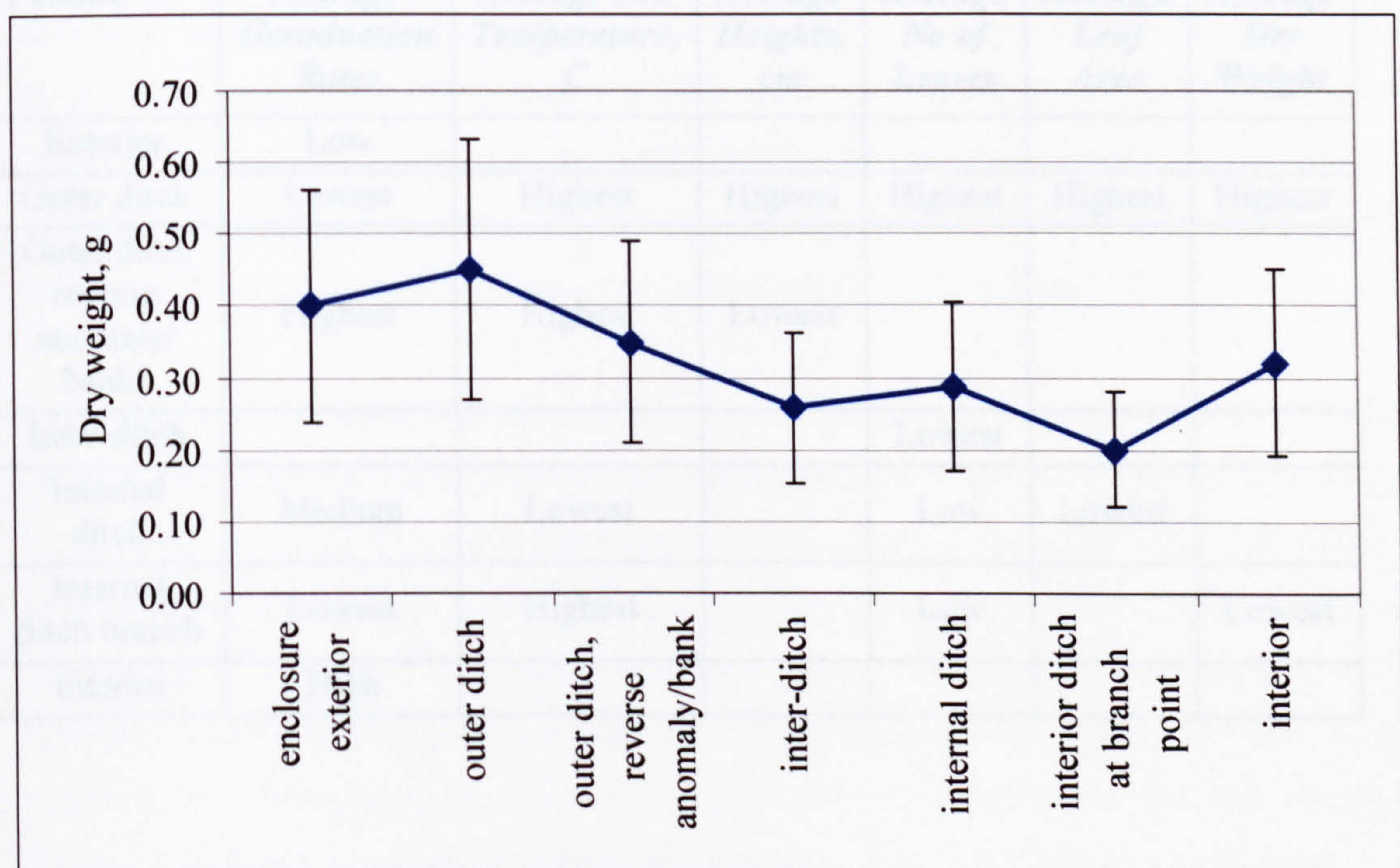


Figure 6.4b:

Mean dry weights of plant at harvest.

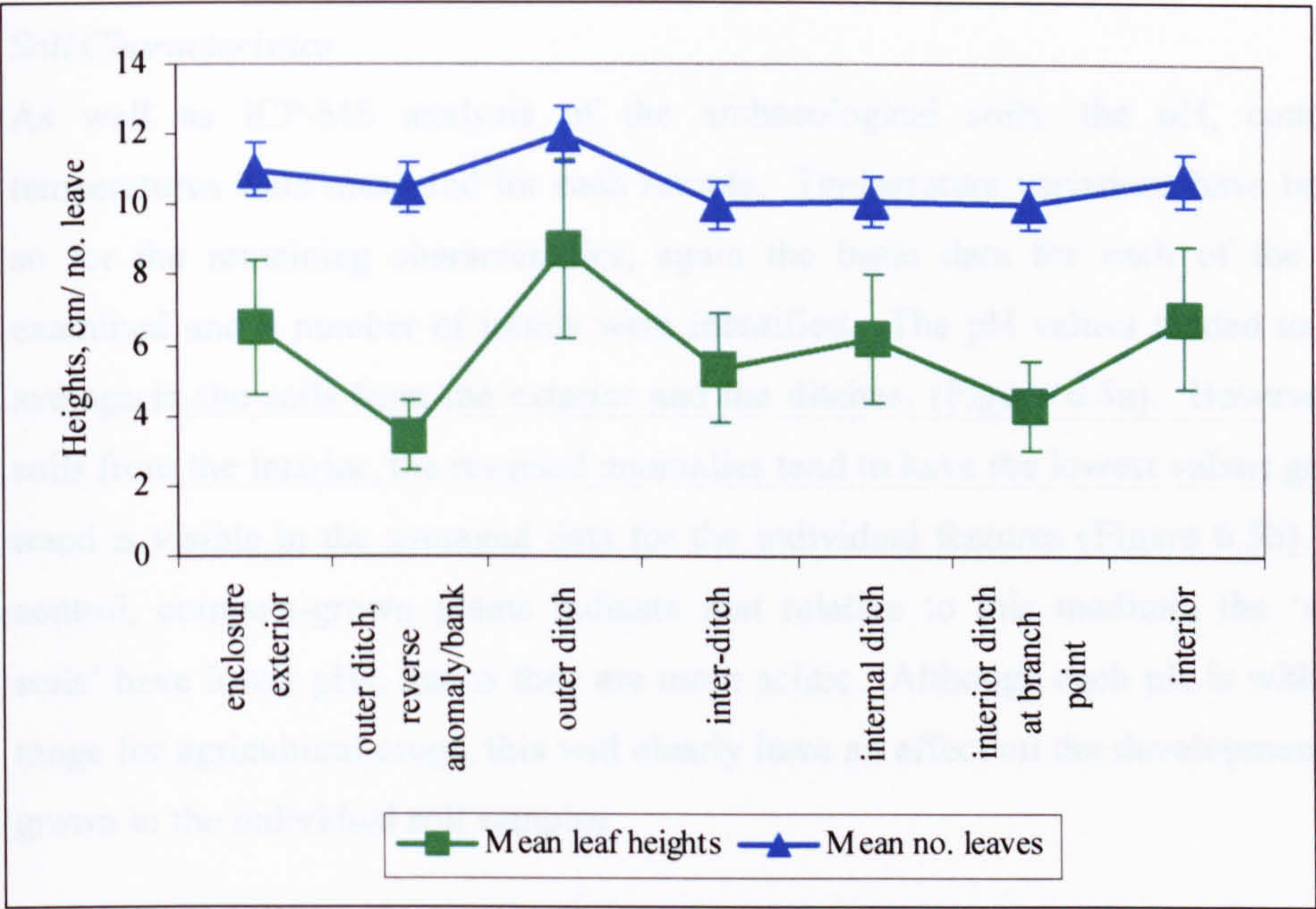


Figure 6.4c:
Mean numbers of leaves and leaf heights.

Table 6.2: Summary of growth characteristics observed in the Experiment 2 plants

Feature	Average Germination Rates	Average Soil Temperature, C	Average Heights, cm	Average No of Leaves	Average Leaf Area	Average Dry Weight
Exterior	Low					
Outer ditch	Lowest	Highest	Highest	Highest	Highest	Highest
Outer ditch reverse anomaly/bank?	Highest	Highest	Lowest			
Inter-ditch				Lowest		
Internal ditch	Medium	Lowest		Low	Lowest	
Internal ditch branch	Lowest	Highest		Low		Lowest
Interior	High					

Soil Characteristics

As well as ICP-MS analysis of the archaeological soils, the pH, conductivity and temperatures were measured for each sample. Temperature variations have been discussed, so for the remaining characteristics, again the basic data for each of the samples was examined and a number of trends were identified. The pH values tended to be higher on average in the soils from the exterior and the ditches (Figure 6.5a). However, along with soils from the interior, the reversed anomalies tend to have the lowest values generally. This trend is visible in the averaged data for the individual features (Figure 6.5b). Data for the control, compost-grown plants indicate that relative to this medium, the ‘archaeological soils’ have lower pHs, that is they are more acidic. Although each pH is within the normal range for agricultural crops, this will clearly have an effect on the development of the plants grown in the individual soil samples

Bench measurements of soil conductivity were also found to be highest externally, with the exception of the branch in the inner ditch. The majority of this ditch, where the conventional geophysical responses were recorded, had a similar conductivity to the exterior of the enclosure. The interior and samples taken from the outer ditch had low conductivities, with the inter-ditch measurements representing an average between the two extremes (Figure 6.6). Table 6.3 summarises all of the information from Experiment 2 up to the point that the elemental analysis of the compositions of the soils and plants is considered, and relates this to the field situation. This includes a comparison of the laboratory measurements of conductivity with the field-gathered resistivity data for the Case Study, and indeed the remaining remotely sensed responses (see Chapter 5). Because of the relative nature of the resistivity measurements however this comparison cannot be fully quantitative.

The table is divided into two; part a) summarises the average responses recorded for the plants grown in soils taken from above the individual features at Case study 2, while part b) explores the predicted field responses expected on the basis of the empirical results relative to those actually recorded. Whilst part a) of the table is relatively self-explanatory, and the characteristics upon which it is based have been discussed in the preceding section and in Chapter 5, part b) requires more consideration. Working from left to right across part b), the expected resistivity signal is based upon measured conductivity for the soil samples. Conductivity is the mathematical inverse of resistivity. They are linked by the equation:

$$S=1/R$$

where: S=conductivity

R= resistivity

(Clark 1990, 34)

The inverse relationship means that wherever conductivity is high, resistivity is low and *vice versa*. The correlation between the two datasets is very good. The results of measurements from the interior are unlikely to correlate very well because there are high and low resistance areas internally which are likely to correspond to features such as dwellings, as discussed in Chapter 5. The main departure from the anticipated and actual results occur where the internal ditch branches into what may be a palisade trench (Chapter 5, pp 175-6).

The anticipated and actual germination rates based upon soil temperature show very little correlation, with only the outer ditch reverse anomaly and internal ditch behaving as predicted. This suggests that soil temperature is not the major factor determining germination rates. As SMC has also been disregarded under these experimental conditions, another explanation must be sought for this phenomenon, but this is outwith the scope of this work.

The plant density based upon the germination rates and translated into field scale densities suggest that the exterior and inter-ditch areas have low plant densities, despite the sowing rate being constant for all soil types, whilst the numbers of plants per metre square increased over the reversed anomaly associated with the outer ditch, the inner ditch and in the interior. A lower plant density is predicted for the outer ditch itself and the branch of the inner ditch.

Calculating the anticipated crop mark type was more difficult, and in this case was based upon the combined characteristics of leaf height, number of leaves and leaf area from part a) of Table 6.3, together with the plant density figures from part b). As with germination rates, this group did not show a very high correlation between anticipated and observed results. An obvious category missing from the characteristics considered was plant colour. Unfortunately this could not be quantified experimentally with the resources available at the time that the work was underway. However, the two features that produced the crop mark type predicted were the outer and inner ditches. This is important as these are generally, and at this site specifically, the features that tend to define crop mark sites.

Most importantly this comparison shows that in general the pot-based experimental results are comparable to field based observations, building confidence in the results. This is important when considering the chemical analyses as it allows the assumption that the results of this work can be applied to field-based situations, despite being removed from the many variables that affect crops growing in the field.

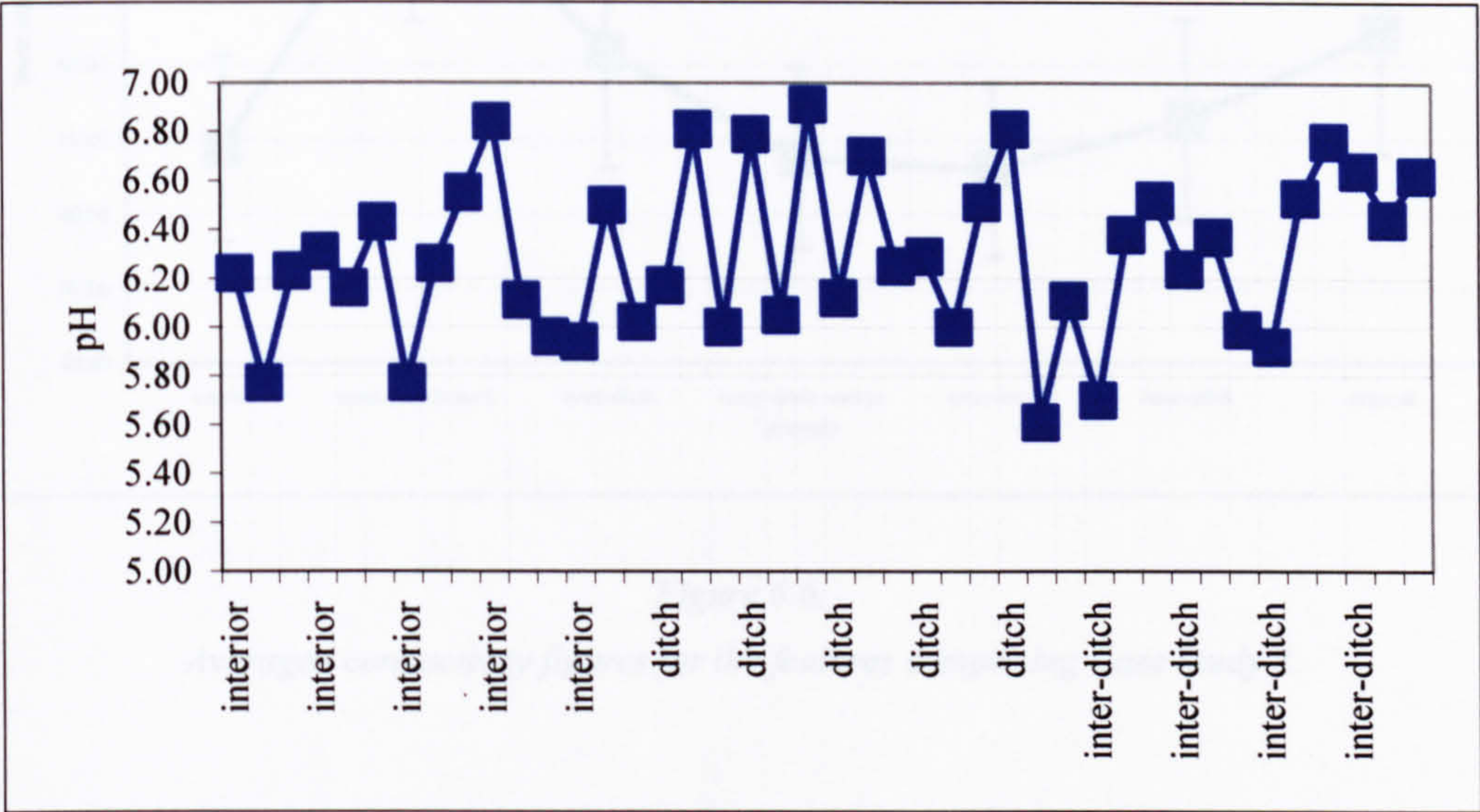


Figure 6.5a:
pH measurements for individual soil samples, by plant pot.

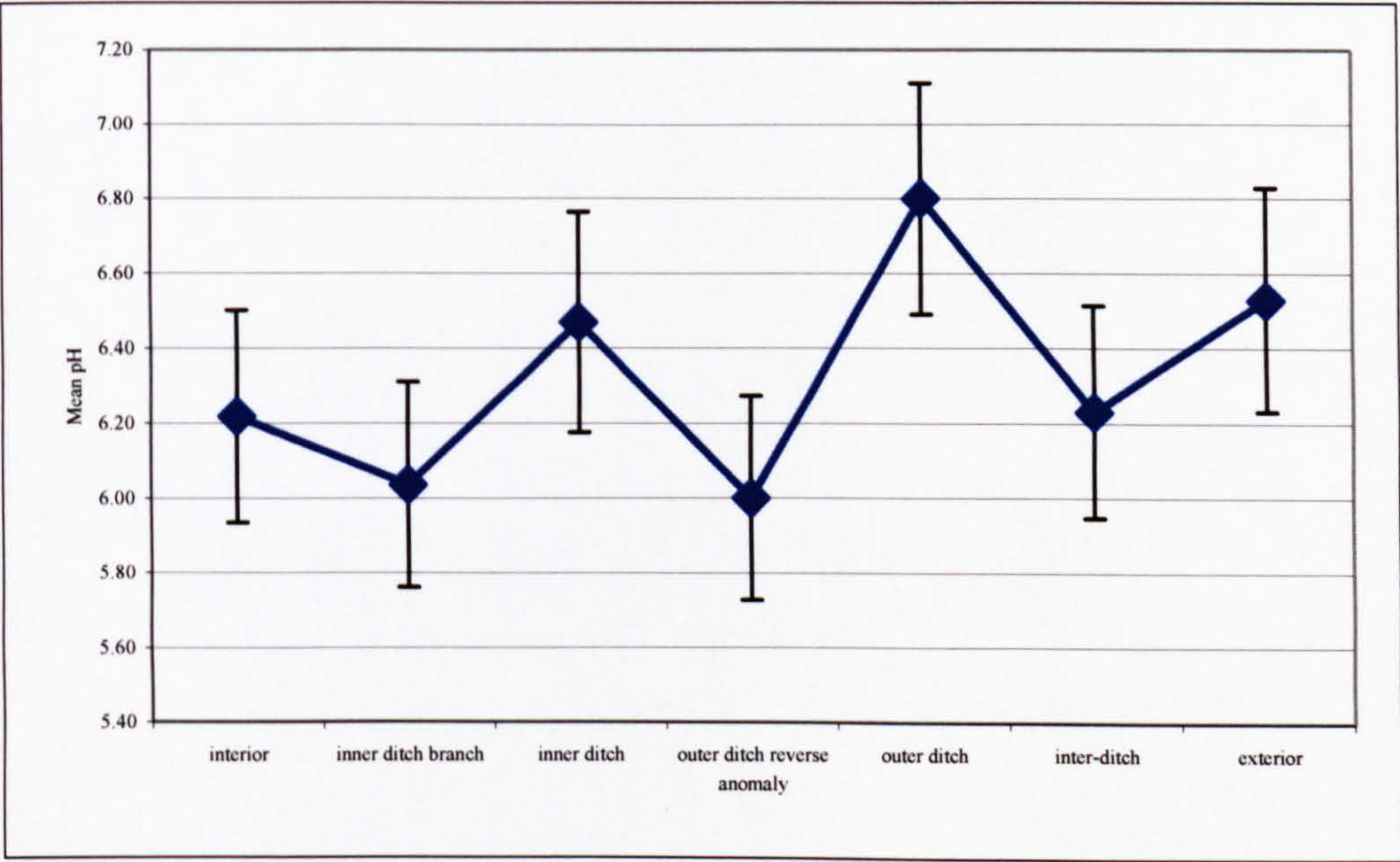


Figure 6.5b:
Mean pH values for each feature sampled.

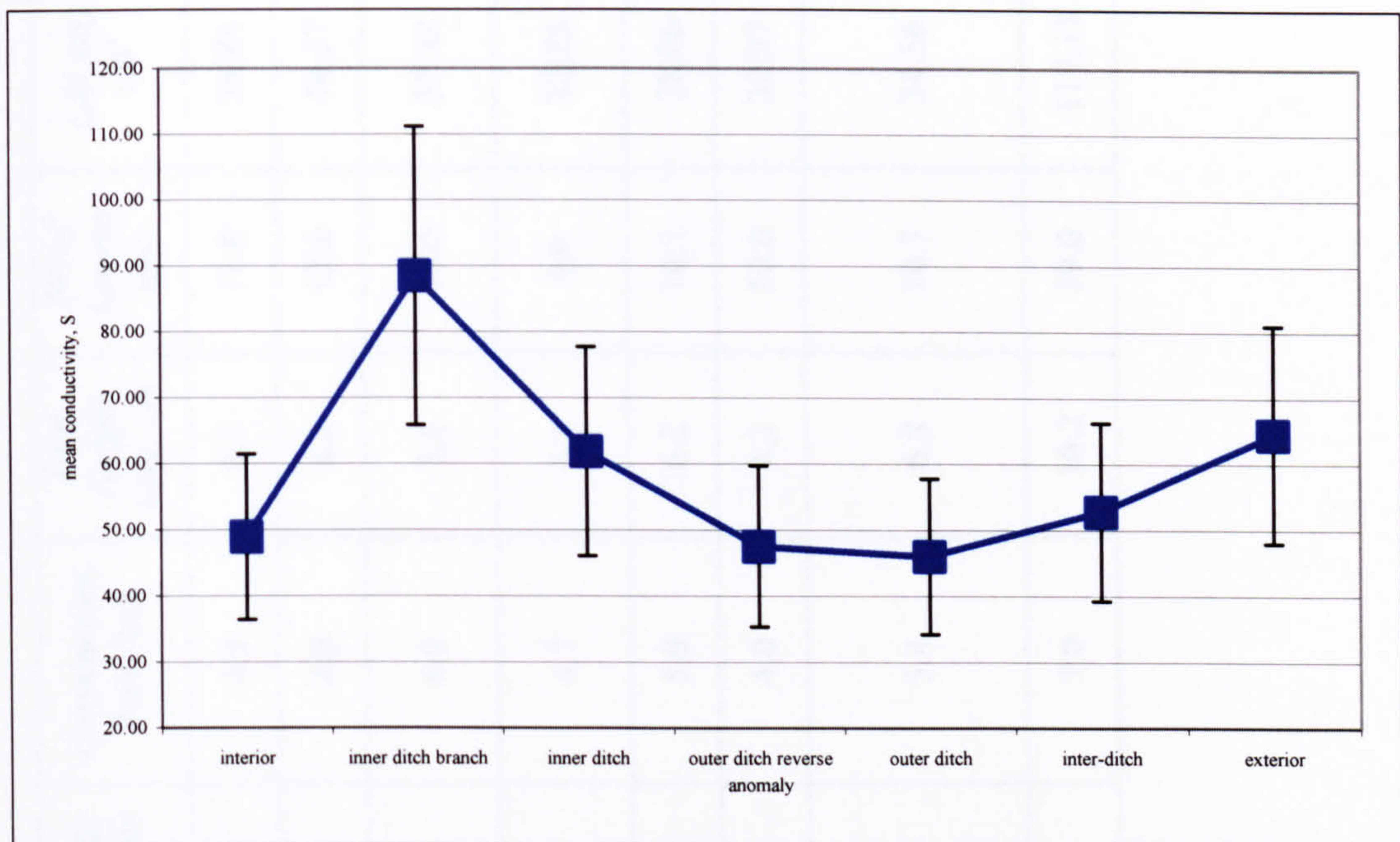


Figure 6.6:
Averaged conductivity figures for the features comprising Case Study 2.

Table 6.3: Summary of Non-analytical Results of Experiment 2

6.3a: Responses Recorded During the Non-analytical Analysis of Case Study 2

Feature	Geophysical Response	Crop Mark Response	Soil Temperature (av) C	pH (av)	Conductivity (av), SI Units	Germination Rate (av)	Leaf Height (av), cm	No of Leaves (av)	LAI (av), cm^2
Exterior	Resistance average; Magnetic average	Positive	28.5	6.53	64.50	4.5	6.5	11.0	36.84
Outer ditch	Resistance high; Magnetic negative	Positive	29.0	6.80	46.00	4.0	8.8	12.0	40.37
Outer ditch reverse anomaly/ bank	Resistance v high; Magnetic positive	Negative	29.0	6.00	47.50	6.0	3.5	10.5	37.32
Inter-ditch	Resistance average; Magnetic average, noisy	Negative	27.9	6.23	52.75	4.7	5.4	9.9	32.23
Internal ditch	Resistance high; Magnetic negative	Positive	29.0	6.04	61.88	5.0	6.2	10.1	28.06
Internal ditch branch	Resistance high; Magnetic negative	Positive	29.0	6.04	88.50	4.0	4.3	10.0	32.97
Interior	Resistance varied high and low patches; Magnetic average noisy	Average, positive and negative areas	28.2	6.22	48.93	5.4	6.8	10.7	34.56
Control	NA	NA	28.0	6.93	46.00	7.0	10.2	19.0	117.13

6.3b: Anticipated Field Responses Based on Experiment 2

Feature	Resistivity Response		GerminationRate		Plant Density per m ² Based on Germination Success	Crop mark response	
	Based Upon Conductivity Measured	Actual Response Measured	Based on Measured Soil Temperatur e	Actual Rate Measured		Based on Growth Characteristics	Actual Response Recorded
Exterior	Low	Average to low	Low	Low	450	~Average	Positive
Outer ditch	High	High	High	Low	400	Positive	Positive
Outer ditch reverse anomaly	High	High	High	High	600	~Positive	Negative
Inter-ditch	Average	Average	High	Low	470	Positive	Negative
Internal ditch	Low	High	Average to high	Average	500	Average to positive	Positive
Internal ditch branch	Very low	High	High	Low	400	Average	Positive
Interior	High	Varied	High	Average	540	Positive	Both
Control	High	na	High	High	700	Positive	na

Chemical Analyses

Soils

The elemental composition of the soils from the individual features in Case Study 2 show noticeable variations. Again, the graphs of individual elemental compositions for each pot were found to be quite difficult to define (see for example Figure 6.7, the chart for Ca), although this data did allow subtle trends to be identified (see also Table 6.4). Accordingly, the remaining results for this experiment and all the remaining analyses are presented as mean data. In this table the ‘Individual Data’ refers to the overview of the concentrations afforded by charting concentrations for each individual sample analysed from the individual features at the site. The ‘Averaged data’ reflects the simplified analysis of the data achieved by plotting the concentration means for each individual sample grouped by feature type. Generally this approach allowed a clearer picture of possible characteristic elemental signatures of the individual features, although in some cases, for example when looking at K concentrations in the ditch fills, it may have been more prudent to separate out the individual ditches to allow differentiation between the two (Figures 6.8 a) and b)). However, as Table 6.4 represents a summary of findings, this level of discrimination is omitted. Because of the large number of elements analysed for, the charts are not presented here, but the raw data for all of the experimental results are included in Appendix 2. Examples of some of the datasets discussed are included here for illustrative purposes however (Figure 6.7 to 6.10). Table 6.4 lists all elements that had concentrations that were thought to be significantly higher or lower relative to the concentrations recorded for the other features at the site, with an indication of those shown to have statistically significant variations. The importance of the identification of raised or lowered elemental levels is that these may, during the course of these experiments, come to be recognised as being indicative of the presence of certain archaeological features. So, for example, for Case Study 2, based upon Table 6.4, higher sodium concentrations, or decreased levels of sulphur could be indicative of the presence of a ditch below the sampling point.

In the individual data, those elements that appear to undergo significant changes in concentration within different features are Mn, Zn and Na. Because certain elements appear to be generally enhanced relative to the exterior of the enclosure, it should be assumed that these elements are also significant, if only from the perspective of their use as a potential prospection tool that can indicate the general existence of a site. The elements grouped in this way include Fe, Mn and Cu. It is interesting that this group of elements has the greatest correlation between per pot and averaged data. Cu, K and Fe appear in the averaged data to

be enhanced over the ditches, although in the case of Cu and K this enhancement is only present over the internal ditch, and for K particularly is most depleted over the outer ditch compared to all the other site features (Figure 6.8). However, the enhancements recorded over the internal ditch may help to explain their appearance as generally raised concentrations in the individual data (Table 6.4), with the averaged data allowing the sources of enhancement to be more clearly defined.

In the averaged data for each group of features sampled, there is obviously correlation with the data for the individual concentrations, but perhaps most importantly, the averaged data highlights some elements that are relatively depleted in certain of the features. For example, between the enclosure ditches Zn has a low concentration overall, with the notable exception of one high reading, while in the interior of the enclosure Na is lower relative to other areas of the site (figures 6.9 and 6.10 respectively). Taking the data as a whole, the soil samples from outside the enclosure have low concentrations of Cd, Co, Cu, Fe, Mg, Mn and Ni (see Figure 6.8b for Cu and K, and Table 6.4). In other words, this group of elements exhibit higher concentrations over the area that contains the site. Conversely, the averaged data shows that Pb concentrations are highest in samples from outside the enclosure, resulting in an overall enhancement on-site of the former group and on-site depletion of the latter. This indicates a set of elements that may potentially be useful as indicator elements whose concentrations change where a plough-levelled site is present, but do not give specific information on feature types or locations in the same way that those changing over individual features may.

Finally, the analytical data from this and the remaining experiments was examined statistically. Using analysis of variance (ANOVA), the variances of the means for the data were calculated, and those elements that were found to vary significantly between groups are indicated alongside the results of the non-statistical examination of the data. The results of the statistical tests are also presented in Appendix 4.

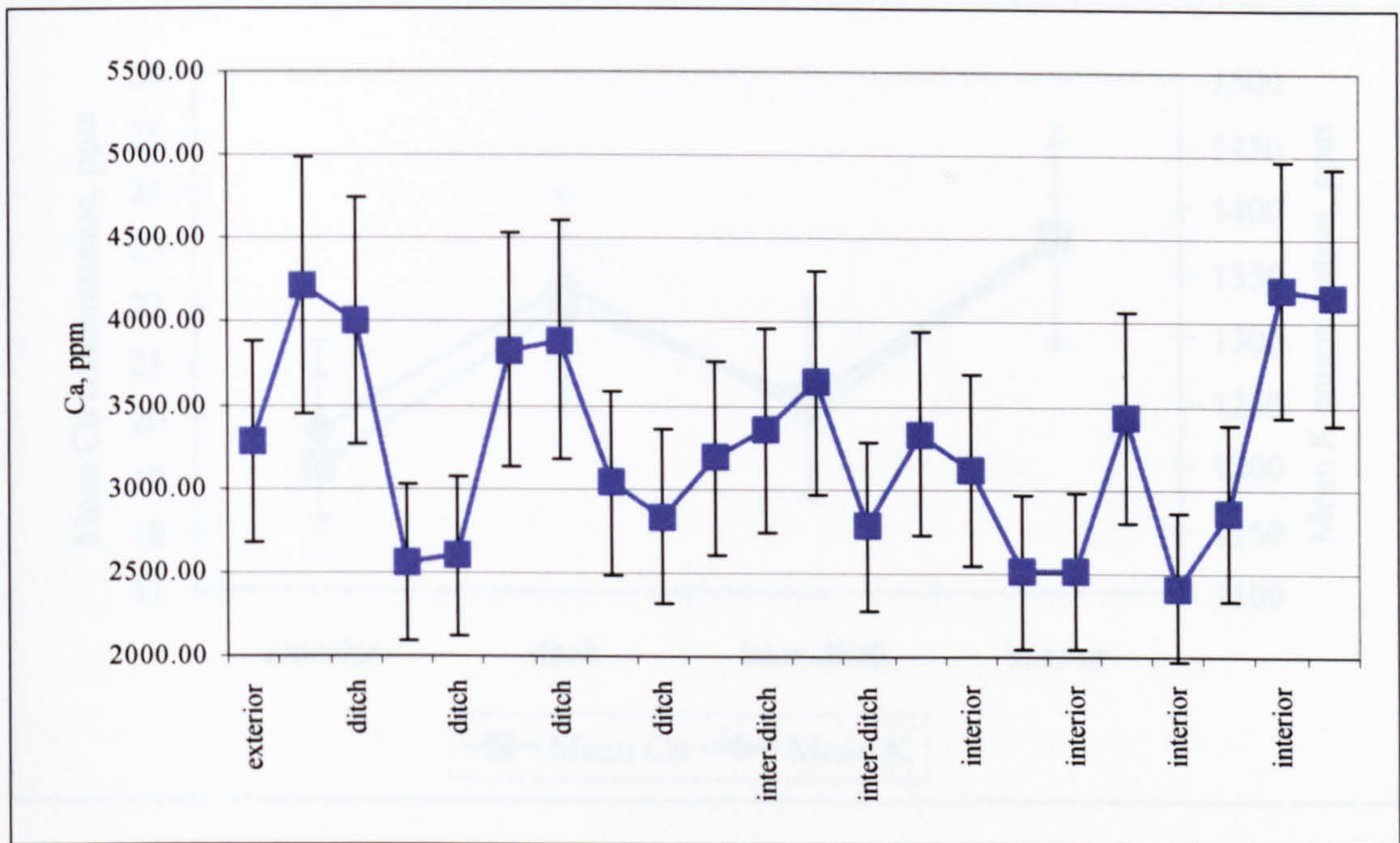


Figure 6.7:
Individual concentrations of Ca.

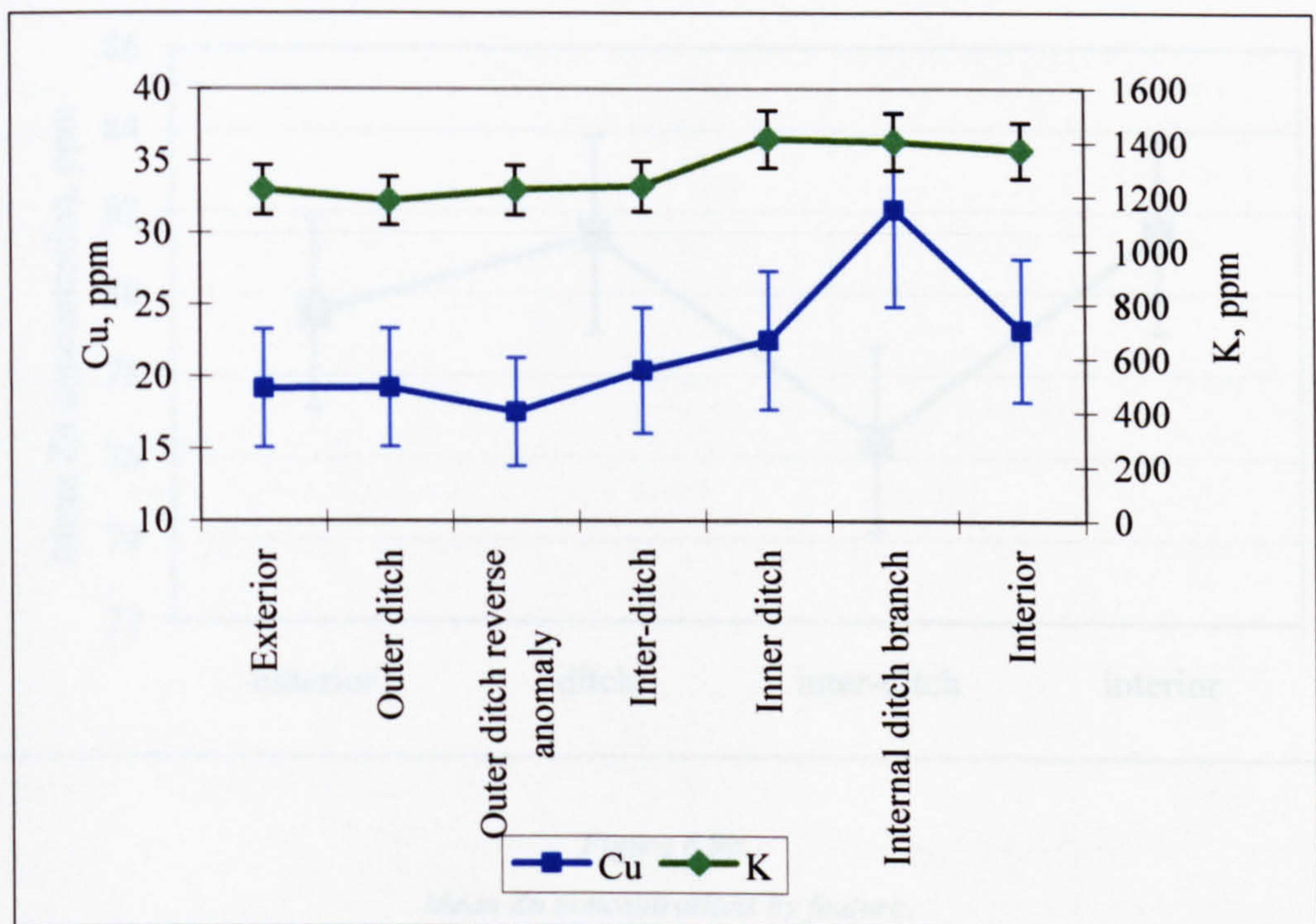


Figure 6.8:
Cu and K concentrations averaged by individual features.

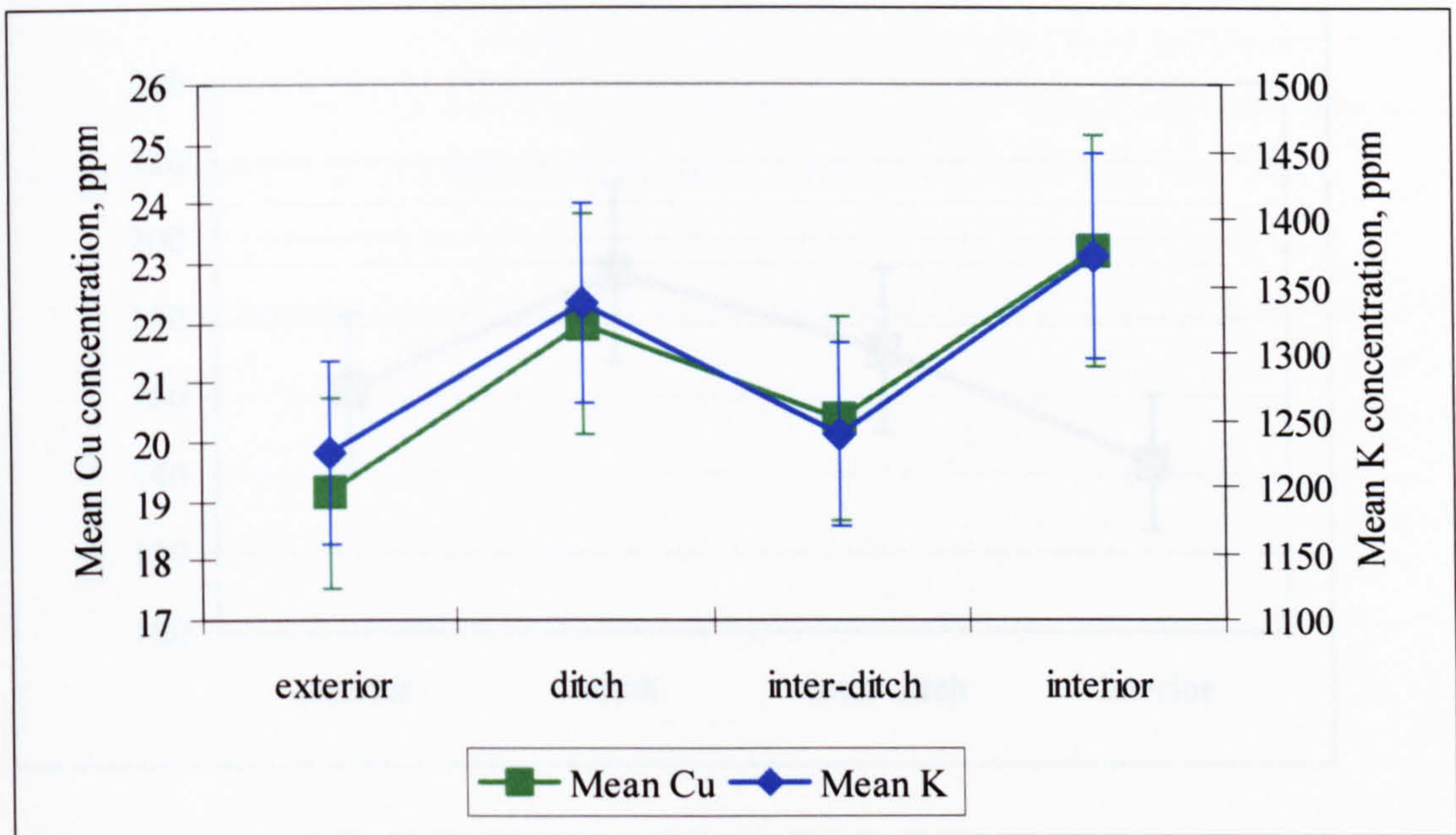


Figure 6.9a:
Mean data for feature types at case Study 2.

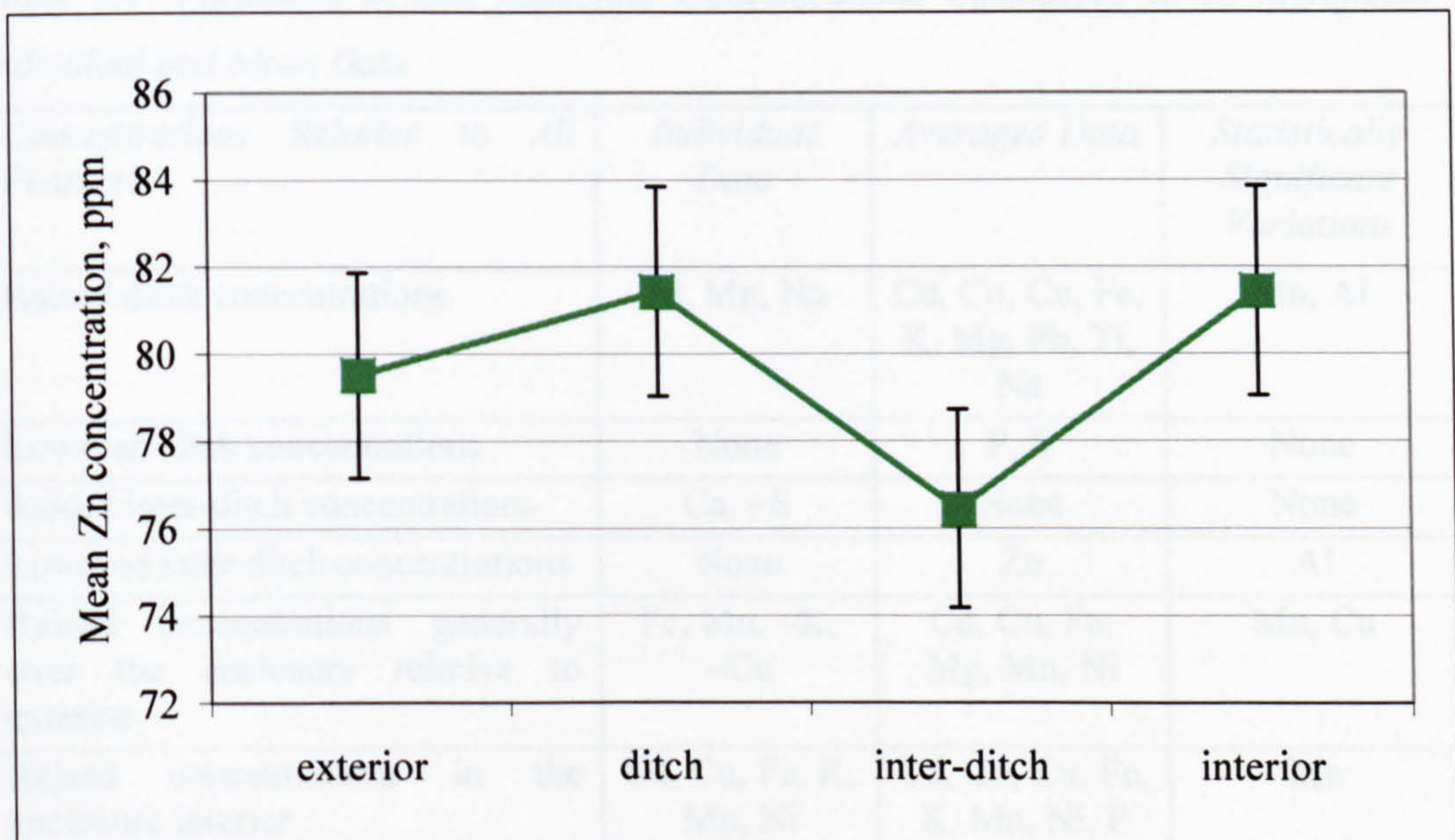


Figure 6.9b:
Mean Zn concentrations by feature.

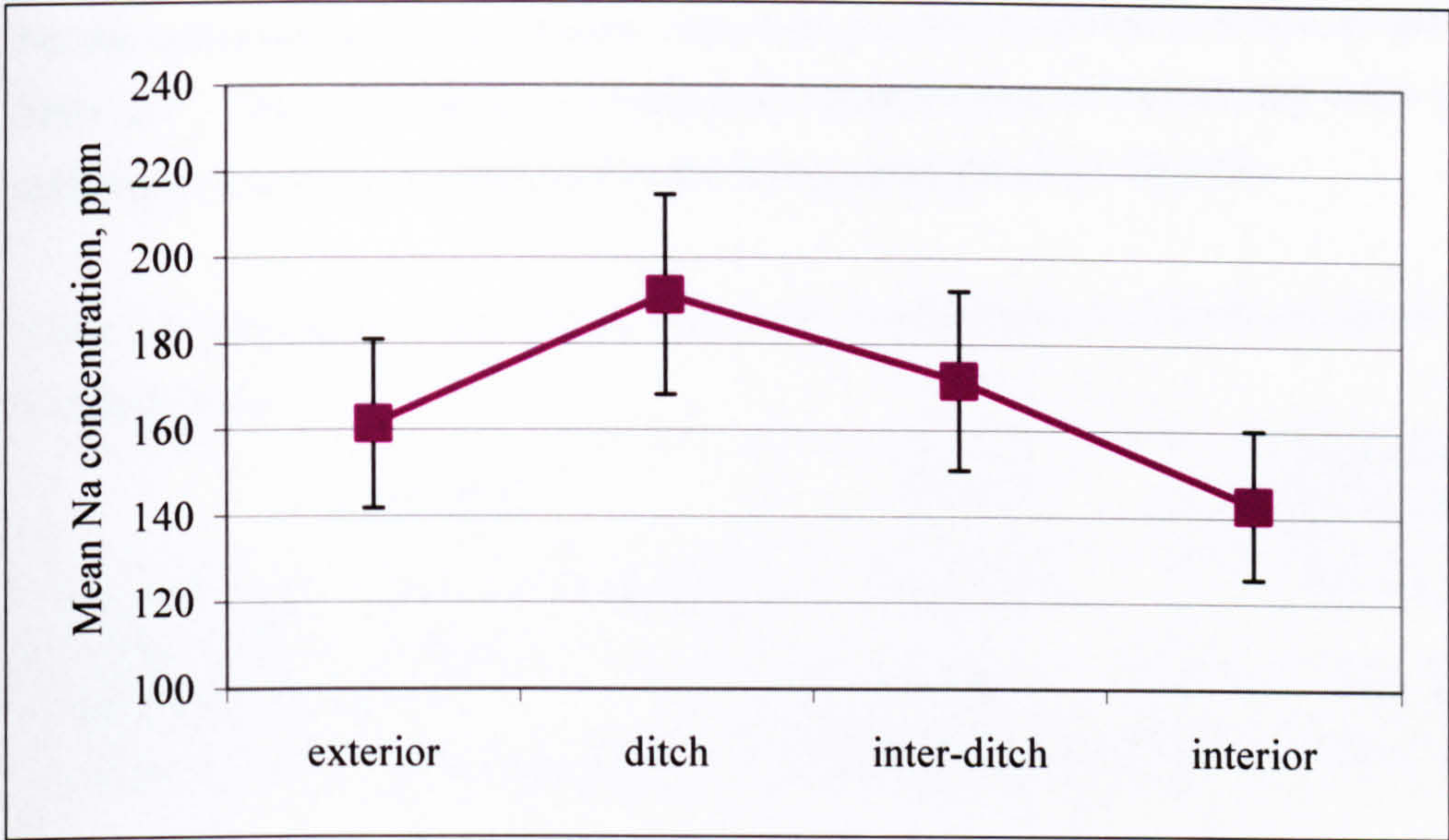


Figure 6.10:
Chart for Mean Na concentrations, and the trend for increased concentrations in the ditch soils relative to other features at the site.

Table 6.4: Variations in Soil Elemental Concentrations Considered to be Significant in Individual and Mean Data

Concentrations Relative to All Features	Individual Data	Averaged Data	Statistically Significant Variations
Raised ditch concentrations	Al, Mn, Na	Cd, Co, Cu, Fe, K, Mg, Pb, Ti, Na	Mn, Al
Lowered ditch concentrations	None	P, S	None
Raised inter-ditch concentrations	Ca, ~S	None	None
Lowered inter-ditch concentrations	None	Zn	Al
Raised concentrations generally over the enclosure relative to exterior	Fe, Mn, ~K, ~Cu	Cd, Cu, Fe, Mg, Mn, Ni	Mn, Cu
Raised concentrations in the enclosure interior	Cd, Cu, Fe, K, Mn, Ni	Cd, Co, Cu, Fe, K, Mn, Ni, P	Mn
Decreased interior concentrations	none	Na	None
Exterior concentrations highest	none	Pb	None
No obvious pattern	Cr, Mg, P, Ti	Al, Ca, Cr,	

For the individual and mean datasets, elemental concentrations that correlate are presented in Table 6.5. The next step was to determine whether these, or indeed any other elemental differences could also be measured in the barley plants grown in the soils.

Table 6.5: Elemental Concentration Variations Considered to be Significant Based on Table 6.4 Information

Concentration	Elements	Statistically Significant Elements
On-site higher relative to background (outside enclosure ditches)	Fe, Mn, Cu	Mn, Al, Cu
Increased over ditches	Na	Mn, Al
Increased in the enclosure interior	Cd, Cu, Fe, K, Mn, Ni	Mn (Cu)

Plants

Again, the differences in elemental concentrations recorded for individual pots within feature groups were found to be as varied as those noted in the data for soils and physical characteristics. Consequently, the data was re-examined using the average values for each feature group. The information from datasets is summarised in Table 6.6. Statistical analysis of the data suggests that there are no statistically significant differences between the means of the concentrations measured in plants grown in soils from the individual features (Appendix 3).

The chemical analyses of the barley plants revealed much more variation in concentrations between features, which is no surprise as plant material is generally a more subtle indicator of nutrient status than soil (D P Moss pers comm.). Averaging the data again made it easier to see trends. Results are not available for Mo, Co, Ti, Ni and unfortunately P for the plant analyses, as these elements show evidence of contamination, resulting in unreliable data, including some negative concentrations. For this reason the analyses have been disregarded throughout.

There is much better correlation between per pot and averaged data for the plant analyses, which illustrates the more obvious patterns of elemental changes between features. Looking at the analytical results in conjunction with the geophysical datasets for Case Study 2 allows the concentrations along each individual augur line to be compared directly with the geophysical anomaly type at that point, which reveals further significant patterns. For

example variations in concentrations can be seen over the (geophysically and aerially determined) ditches for Al, Fe, K, Mg, Mn, Zn and Na, with all but K and Mn having elevated concentrations for both inner and outer ditches (Figure 6.11). Levels of Zn are high in the enclosure interior and generally elevated relative to the enclosure exterior.

Concentrations of elements in the soil samples compared to the geophysical anomalies reveal that the ditches generally show increases in Co, Fe, Mg, Mn, ~K and Na, and relatively depleted concentrations for S and Cu (Figure 6.12). Elevated levels of Fe, K, Zn and Mg were recorded in the interior of the enclosure (although this is depleted for the line 20 samples) and Zn. Table 6.7 summarises the elements that appear to have significant concentration changes in different features at this site for plant and soil analyses.

Table 6.6a: Individual and Mean Concentrations for the Plant Analyses

<i>Concentration Variation</i>	<i>Individual Values</i>	<i>Averaged Data</i>
Raised ditch concentrations	Mg, Mn	Al, Ca, Cr, Cu, Fe, Mg, Na
Lowered ditch concentrations	none	Mn,
Raised inter-ditch concentrations	Zn	K, ~Zn
Lowered inter-ditch concentrations	Al, ~Fe	Al, Cr, Fe, Mn, Na
Raised interior concentrations	~Fe, Mn, S	Mn, Na, S
Decreased interior concentrations	none	none
Exterior concentrations lowest	none	Ca, Mg, Pb, S
Exterior concentrations highest	none	Mn
No obvious pattern	Ca, Cr, Cu, K, Pb	none
No reliable data	Mo, Co, P, Ti, Ni	

Table 6.6b: Statistically Significant Elemental Concentrations

Raised ditch concentrations	Mg
Raised inter-ditch concentrations	Zn
Lowered inter-ditch concentrations	Al, Fe
Raised interior concentrations	Mn

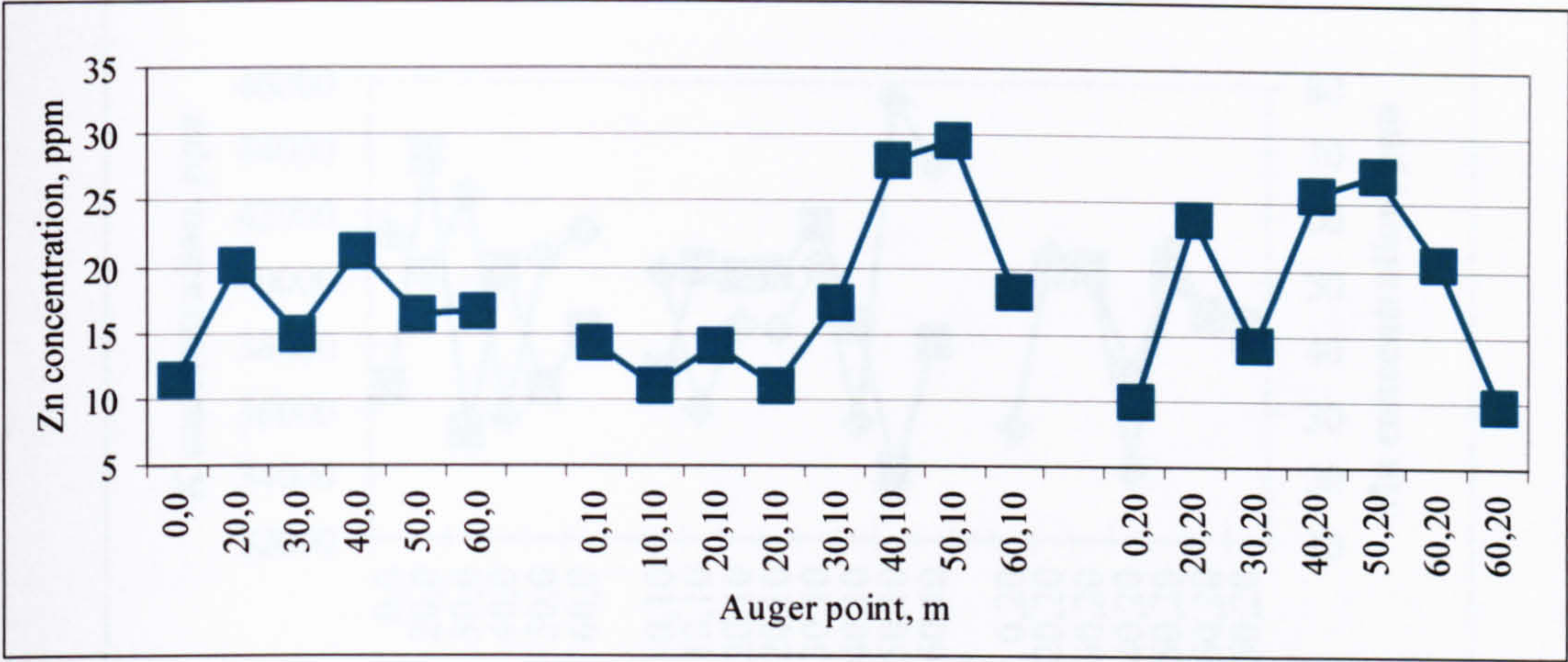


Figure 6.11a:
Changing concentrations in plant analyses along augur lines for Zn.

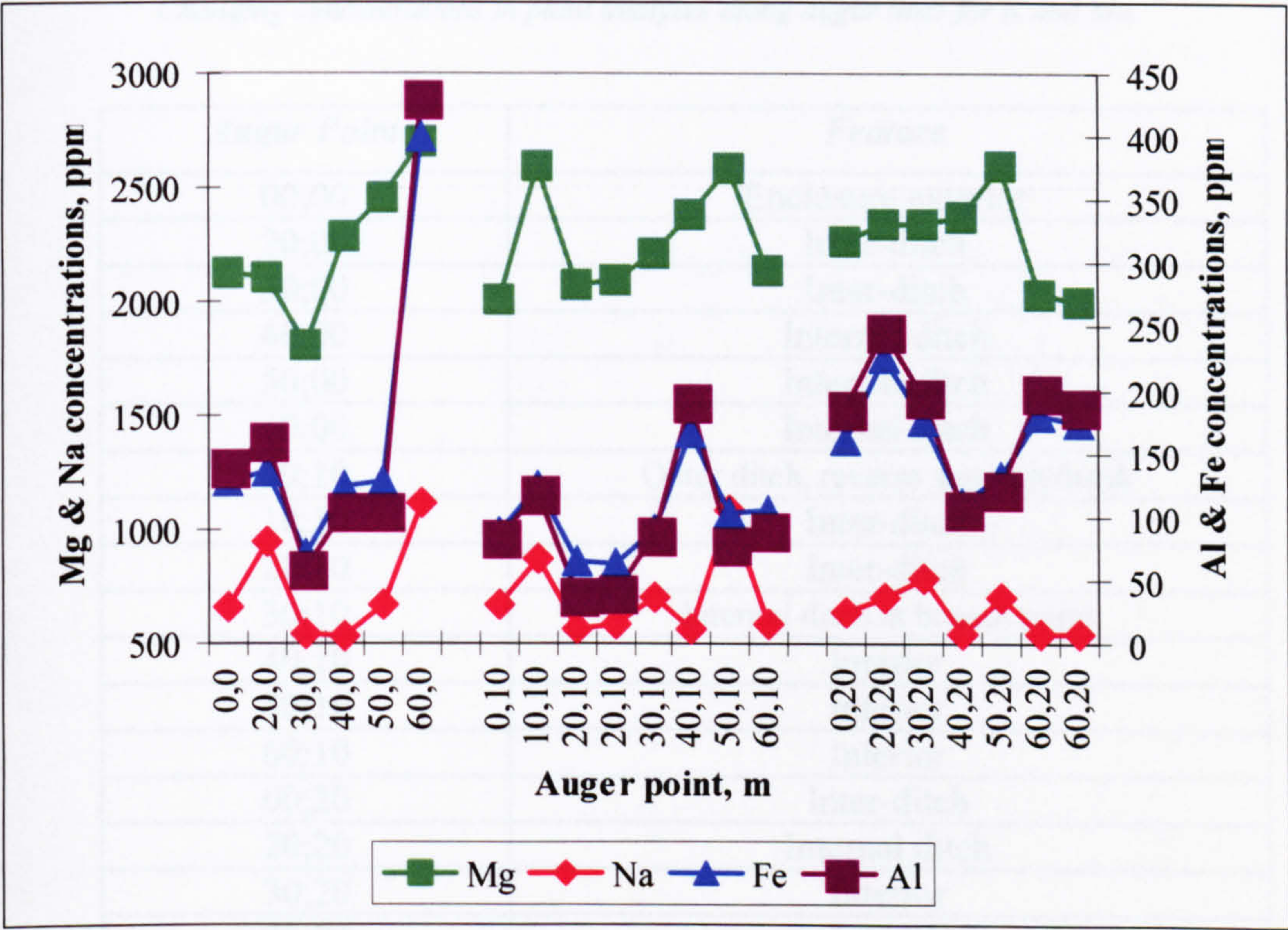


Figure 6.11b:
Changing concentrations in plant analyses along augur lines for Mg, Na, Fe and Al.

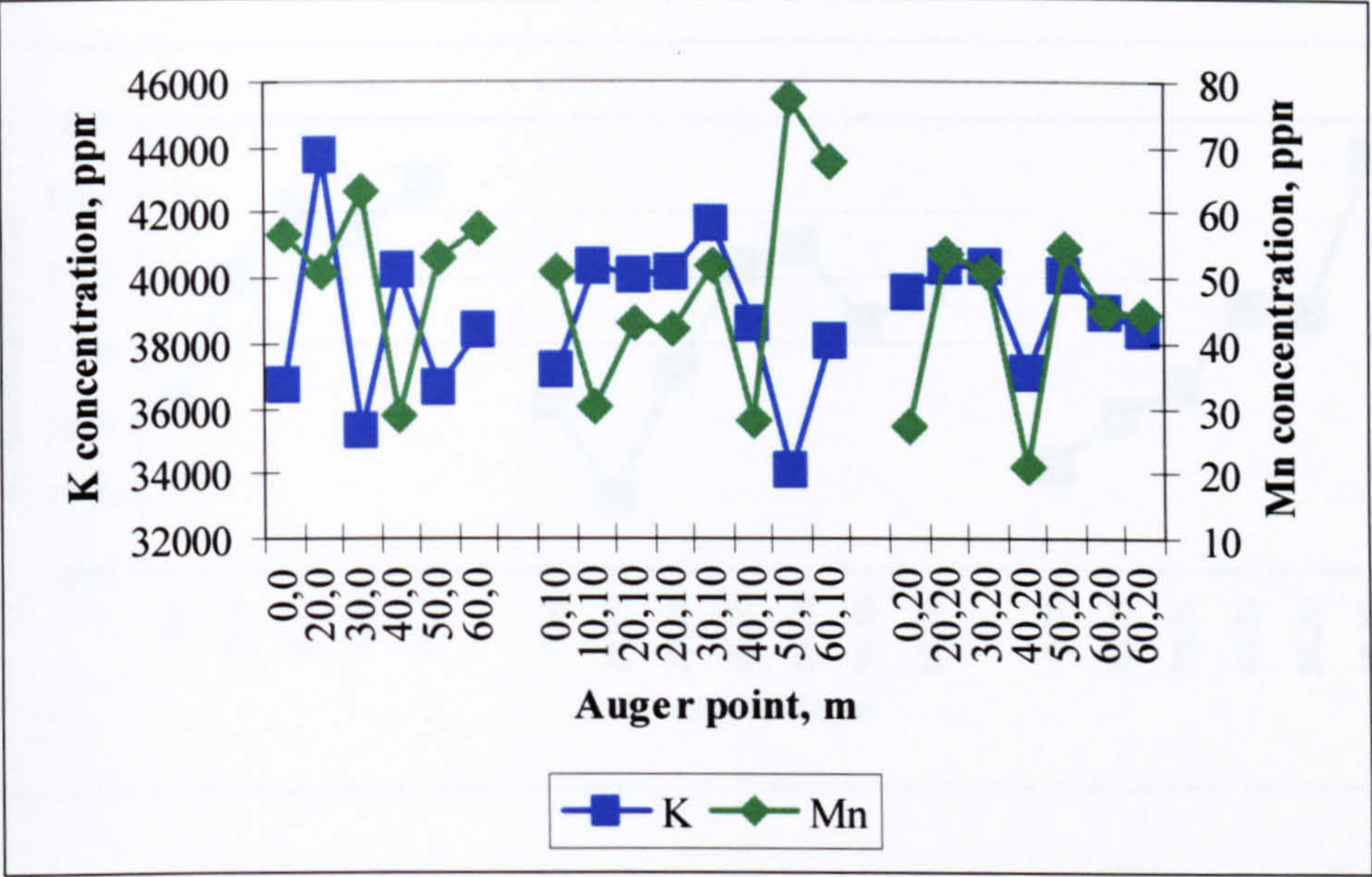


Figure 6.11c:
Changing concentrations in plant analyses along augur lines for K and Mn.

Augur Point	Feature
00;00	Enclosure exterior
20;00	Inter-ditch
30;00	Inter-ditch
40;00	Internal ditch
50;00	Internal ditch
60;00	Internal ditch
00;10	Outer ditch, reverse anomaly/bank
10;10	Inter-ditch
20;10	Inter-ditch
30;10	Internal ditch at branch point
40;10	Interior
50;10	Interior
60;10	Interior
00;20	Inter-ditch
20;20	Internal ditch
30;20	Interior
40;20	Interior
50;20	Interior
60;20	Interior

Figure 6.11:
Plant elemental concentrations along the auger sampling points at Case Study 2, with accompanying table indicating features over which the augur samples were taken.

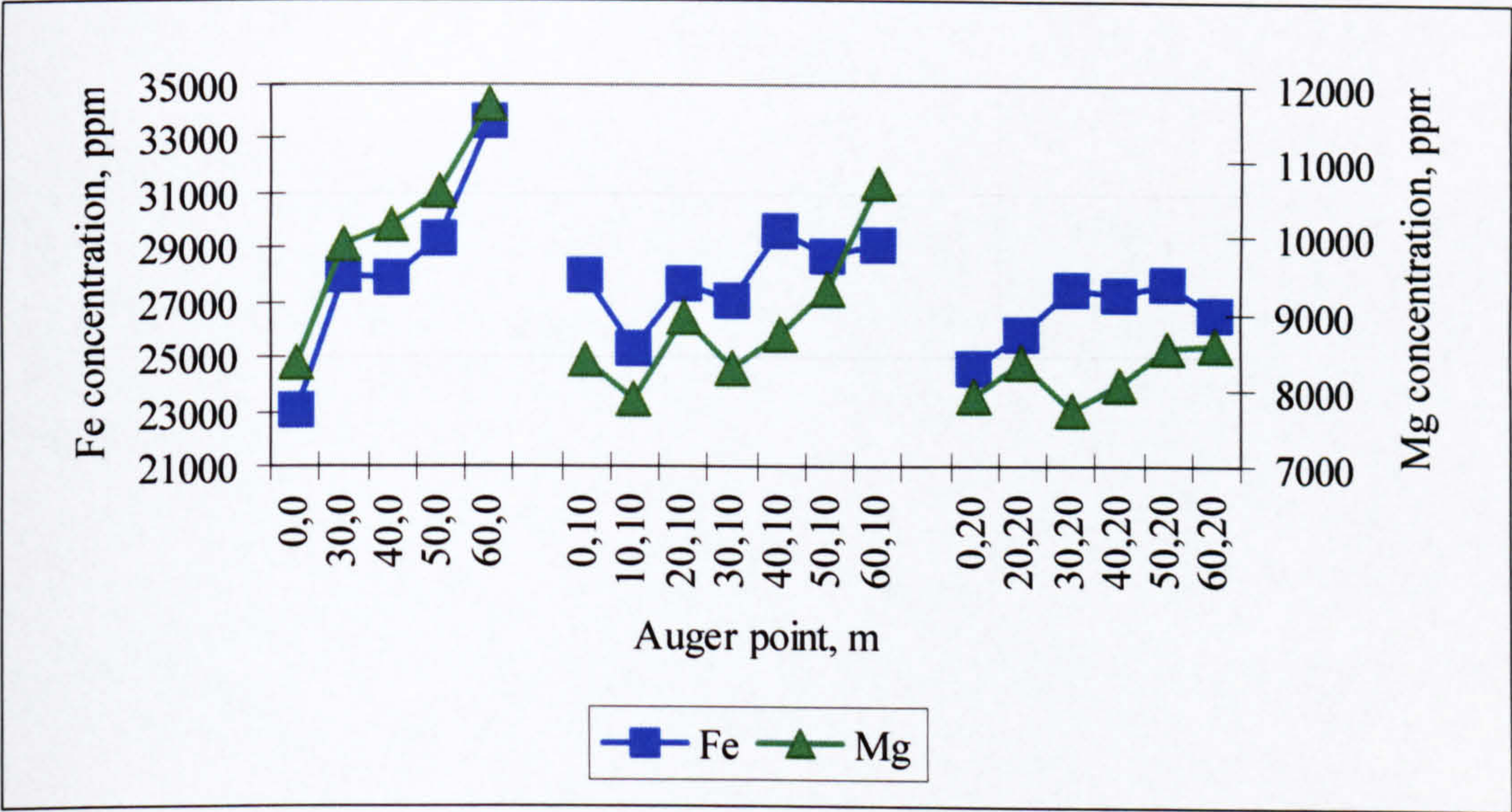
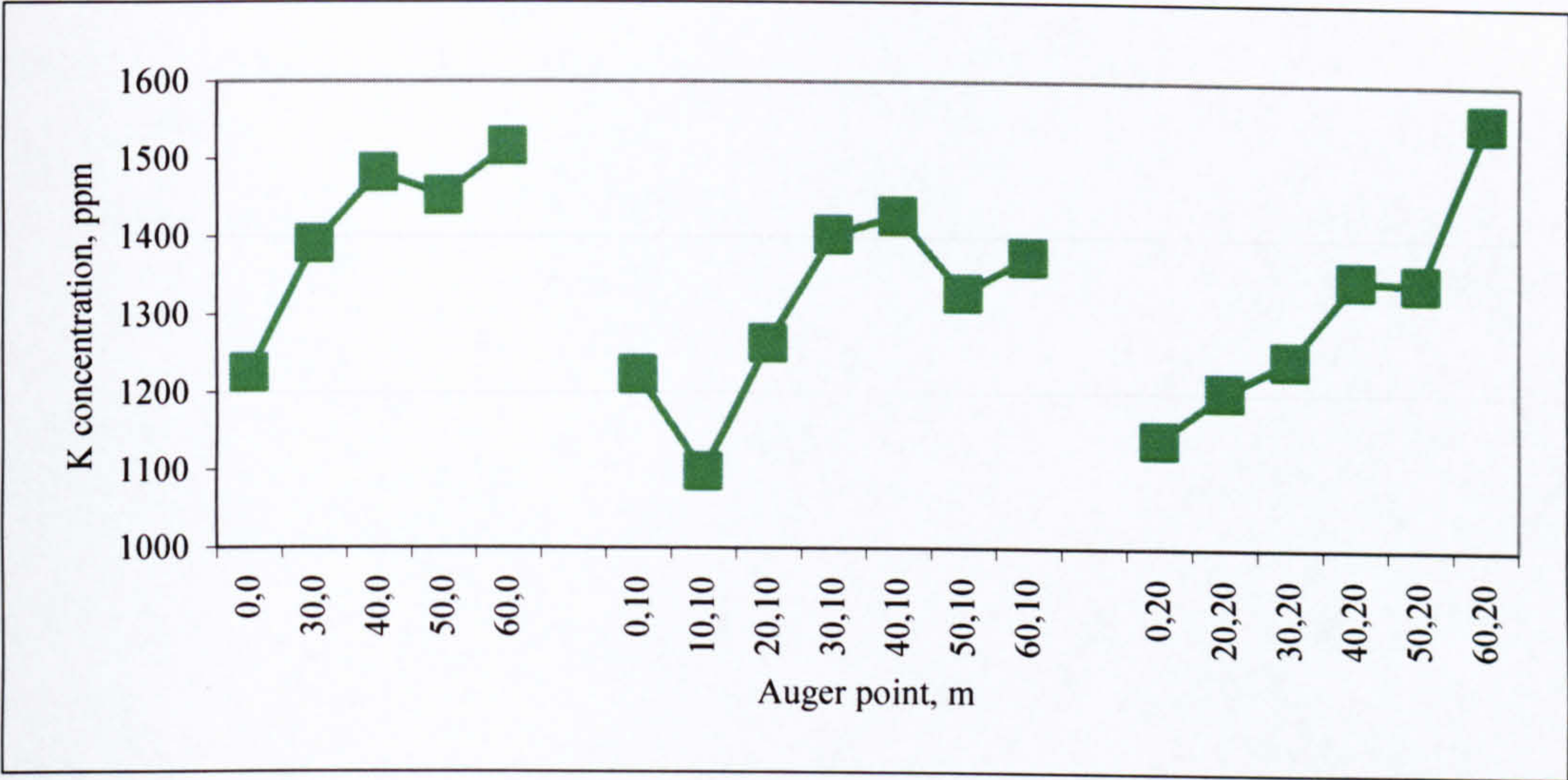


Figure 6.12:
Variation in soil concentrations along the auger lines. Augured features are as described for Figure 6.11.

Table 6.7: Summary of Significant Elements Identified in Soil and Plant Samples from the Different Enclosure Features Relative to Geophysical Anomalies

Concentration	Plants	Soils	Geophysical Anomaly
Raised above ditch	Mg, Fe, Al, ~Cu, ~Zn, ~Na	Mn, Mg, Na, Fe. ~Cd, ~K, ~Pb	Resistivity: High; Magnetic: Negative
Lower above ditch	Mn, K	~S, ~Cu	Resistivity: High; Magnetic: Negative
Raised above inter-ditch	Zn	~S	Resistivity Average, Magnetic noisy average
Lower above inter-ditch	Al, Fe, ~Mn, ~Na	Zn	Resistivity Average; Magnetic noisy average
Raised above interior	Mn, S, ~Zn, ~Fe, ~Na	Cd, Cu, Fe, K, Mg, Mn, ~Zn	Resistivity varied; Magnetic noisy average
Lower above interior	None	Na	Resistivity varied; Magnetic noisy average
Raised above Exterior	Mn	Pb	Both average
Lower above Exterior	Mg, S, ~Zn	Fe, Mn, ~K, ~Cu Cd, Ni	Both average
No obvious pattern	Ca, Cr, Pb	Cr, Al, Ca	NA

A Summary of Results from Experiment 2

Table 6.8 provides a summary of all the results from Experiment 2. While a brief statement on their significance is included here, the final results of this and the remaining experimental work will be considered in greatest detail when they are all brought together in the concluding part of this chapter, and in the discussion and conclusions on the thesis in its entirety in Chapter 7. This bringing together of results from the five experiments and three case studies is considered to be the most likely place that significant conclusions will be drawn about the nature of remotely sensed responses to crop mark sites generally, and this is where the answers to the questions posed in Chapter one are expected to lie.

At this site positive crop marks are associated with negative magnetic anomalies. High resistivity readings also correlate with positive crop marks, which is generally considered to be the reverse of the expected response, but see Clark (1990, 49-53), and the one negative crop mark investigated produced a very high resistance and a positive magnetic anomaly. Aside from the correlation between resistivity and conductivity values, which as discussed earlier have an inverse relationship, there is no obvious relationship between conductivity and either crop mark appearance or magnetic responses. Similarly, no direct relationship can be identified with pH and the preceding responses.

Germination rates tend to correlate inversely with anticipated crop mark responses for the features, with positive crop marks tending to coincide with low germination rates, which is not the result that would commonly be expected. Magnetic responses and germination rates show a loosely correlating relationship, with soil from the positive reverse anomaly of the outer ditch being the only feature to support a high germination rate. This loose correlation with germination rates also extends to the resistivity data, with this anomaly being the only (positive) one to produce a high resistivity response. Given the very different responses to this feature its tentative interpretation as the remains of a bank made in Chapter 5 can still not be discounted on the basis of the remotely sensed and experimental evidence.

The germination rates exhibit an inverse relationship with pH for all but the inner ditch features. For the remaining growth characteristics there appears to be a higher correlation between the outer features; the exterior, outer ditch components and the inter-ditch, than that recognised for the inner ditch and interior. It is difficult to say anything specific about the interior because of its inhomogeneous appearance on crop marks and geophysical plots, which is assumed to contain features associated with habitation, but which cannot be clearly resolved or located accurately enough to allow more specific comments.

Of the chemical analyses it is hard to generalise on the basis of one experiment, because as Table 6.8 indicates, many of the elements investigated exhibit enhancements or depletions in both the soils and the plants. As the database of experimental work accumulates during this chapter these results will be returned to in the hope that patterns of elements that are indicative of features at more than one of the Case studies will emerge. With this in mind it is interesting to note that of the plant analyses the ditches tend to have elevated Mg and depleted Mn levels. Al is depleted in the plants grown in soils from the inner ditch branch and the inter-ditch, and this correlates with the mean Al concentrations calculated statistically (Appendix 3). The ditches again feature similarly concentrated elements amongst the soil results, with Mg, Pb, Na and Ti elevated in both the inner and outer ditch soils. Relative to the crop marks Pb is concentrated in all of the features that produce positive marks. Conversely Fe is depleted in the plants analysed from the outer and inter-ditch components.

Statistically, elements showing mean differences in concentration between features that are more pronounced than would be expected by chance alone include Al, Cu and Mn. For Mn and Cu, the point sampled where the inner ditch branches into two is particularly enhanced

relative to all of the other features sampled, and is higher than the concentrations measured over the main inner ditch anomaly. Conversely the reverse anomaly recorded geophysically at the outer ditch is depleted relative to the soil samples taken from the main outer ditch anomaly. This suggests that elemental differences do at least play a part in the geophysical responses recorded at this site. For Al the inner and outer ditches are both enhanced relative to all of the other features sampled.

Although no simple relationship is revealed in the overall results from Experiment 2, they are a reminder of the complexity of the questions asked in this thesis, but also indicate that the soil characteristics and specifically conductivity, pH and to a lesser degree soil temperature, do vary with context. There are also variations in elemental concentrations, which may or may not reflect the pH and conductivity differences, for example low conductivity appears to correlate with higher Mg in both soil and plant samples, except where the outer ditch anomaly reverses and the inner ditch branches, where in both cases it is depleted. Cu appears to be depleted in soil samples that have higher pH values. It is difficult to say whether this is an anthropogenic or pedological effect, but what is important about these results is that they are definitely not due to differential moisture levels as far as provision of water is concerned, as this variable was eliminated in the experimental set-up. However, although the ability of the individual contexts to retain water differentially was not investigated and so SMC differences due to soil structural and textural changes cannot be ruled out, and provides the material for an entirely separate thesis, this indicates, as far as it can within this work, that soil moisture is not the only factor that must be considered in either crop mark formation or the development of resistivity anomalies, as the review of the evidence in Chapter 2 suggests.

A group of elements exist in the averaged soils data that display a trend towards high concentrations in the ditches and interior, and a low external concentration. These elements are Co, Cu, Fe, Mn, Ni, and to a lesser degree K and Cd. They appear to have the potential to indicate areas of sites that contain negative features such as ditches and areas that lie topographically lower than the accompanying site remains, for example enclosure interiors. Pb concentrations are highest in samples from outside the enclosure, resulting in an overall enhancement on-site of the former group and on-site depletion of the latter. If proven and developed this may be a useful prospection method in areas that do not traditionally produce crop marks, assuming that these differences can also arise without altering growth, with this set of elements being potentially be useful as indicator elements whose concentrations

change where a plough-levelled site is present, but do not give specific information on feature types or locations in the same way that those changing over individual features may. However, this is just one area sampled from one site and so this assumption must be treated with extreme caution until more data can be gathered and assessed. Despite the small-scale of the experimental work carried out for this thesis, it will still be possible to determine whether these elements play a similarly potentially important indicative role at the remaining two case studies.

In the averaged data for each group of features sampled, there is obviously correlation with the data for the individual concentrations, but perhaps most importantly, the averaged data highlights some elements that are relatively depleted in certain of the features. For example, between the enclosure ditches Zn has a low concentration, while in the interior of the enclosure Na is lower relative to other areas of the site (figures 6.9 and 6.10 respectively, Figure 6.8a for Cu and K, and Table 6.4).

Comparing the individual and averaged data results, those elements that appear to be significant in both datasets are Fe, Mn and Cu. As these are all transition elements this could indicate that soil chemical differences, related perhaps to soil moisture retention differences, exist on- and off-site, causing changes in aeration and thus pH and redox potential, as well as elemental mobility as discussed in Chapter 2 (80-1). These changes have various effects on the behaviour of these elements within the soil-plant system, depending on chemical species and soil environment. Resultant behaviour can include the locking of the elements into the soil either in the soil water or as adsorbed particles on clays, moving away of the elements from the topsoil by leaching, or making them available to plants for uptake and assimilation with soil water. Such changes can also shift chemical equilibria within the soil, for example by causing one of the elements to become oxidised or reduced, its bioavailability also changes, moving its soil equilibrium constant and therefore mobilising it within the soil or removing it from the available pool. Changing concentrations may be ‘simply’ a consequence of soil chemical processes and equilibria, or could represent existing anthropogenic inputs to the soil system. Either way it is clear from these results that elemental differences do exist, at least at Case Study 2. These differences are likely to affect crop appearance and also influence geophysical results. As Fe and Mn can substitute for each other in crystal lattices and Fe, and to a lesser extent Cu, are important contributors to soil magnetism and can conduct electricity, this would explain the correlation of the

magnetic data with the resistivity and aerial photographic results for this site, discussed in greater detail below.

From Table 6.7 it would appear that Fe and Mg, and to a lesser extent Na, Mn and K, which contrary to the other elements are depleted in plant and raised in soil samples over the ditches, are significant indicators of the ditch sampled at Case Study 2. In the inter-ditch areas Zn concentrations are raised in the plants analysed and depleted in the soils, and this pattern can also be seen for Cu in the ditch results. This is discussed in the concluding section of this chapter. This inverse relationship is also noted for Na in the samples analysed from the enclosure interior (plants high, soils low), where Mn and to a lesser extent Zn and Fe concentrations show evidence of being systematically raised relative to those measured in the samples from the other features. For samples analysed from outside the enclosure the inverse relationship between plant (raised) and soil (lowered) concentrations is again seen, this time for Mn, which is the only (inversely) correlating element noted for the area outside the outer enclosure ditch.

Where concentrations are high in plants but present in low concentrations in the soil samples analysed, it suggests that the element concerned is easily available for uptake. This is discussed further in the concluding sections of this chapter, and this is likely to be due to soil chemistry and the way the element is held in the soils, perhaps associated with anthropogenic alteration of the soil due to on-site activities. Where concentrations are high in soils and low in plants this could simply be due to a limited requirement for the element by the plant (i.e. a trace element), or it could be limited in the soil despite being present in measurable quantities because the element is not held in a form usable by the plant. However, it should be noted that higher soil than plant concentrations are an expected outcome generally.

Statistical analysis suggests that while none of the altered concentrations measured in the plant material differ significantly enough about their means to be more than the result of chance variations, there are significant variations in the concentrations of Mn, Al and Cu in the soils.

Table 6.8: Summary of Results of Experiment 2

Feature	Crop Mark	Magnetic Response	Resistivity Response	Conductivity	pH	Enhanced Elements			Depleted Elements		Soil Temp	Germination	No of Leaves	Leaf ht	Leaf Area
						Plant	Soil		Plant	Soil					
Exterior	Positive	Average	Average to low	High	High	Mn	Pb		S, ~Zn	Fe Mn Cd ~K ~Cu Ni	Av.	Low	High	Tall	Large
Outer ditch	Positive	Negative	High	Lowest	High	Mg	~Mg, Pb ~Na, Ti ~Cd		Mn, K, ~Fe, ~Zn	Cu	High	Low	Highest	Tall	Large
Outer ditch reverse anomaly	Negative	Positive	Very high	Low	Low	none	Fe		Mg Fe, Zn	Mn	High	High	Average	Short	Large
Inter-ditch	Average	Noisy av.	Average	Average	Av.	Zn	~S		Al, Fe, ~Mn	Zn	Av.	Low	Lowest	Av.	Av.
Inner ditch	Positive	Negative	High	Low	Low	Mg Fe Al Cu Na	~Co K Mg Pb ~Ti ~Na Mn		Mn	P, ~S	Low	Average	Average	Av.	Small
Inner ditch branch	Positive	Negative	High	Highest	Low	none	K, Mn P Pb		Al	Mg	High	Low	Lowest	Short	Av.
Interior	Both	Noisy average	Both	Low	Av.	Mn S ~Zn ~Fe ~Na	Cd ~Co Cu Fe K Mn Ni P ~Zn Mg		none	Na	Av.	Average	High	Tall	Av.

6.4 Experiment 3: Growth of Spring Barley in Archaeological Soils Under Differing Watering Regimes

Following on from the assessment of growth characteristics of barley plants from Case Study 2 that revealed growth differences in the mean data most clearly, we come to Experiment 3. In this investigation, soils from Case Study 1 were used in a similar experimental set-up to that of Experiment 2, and the same growth responses were recorded, but here 2 extra pots per sample were set up. This allowed not only a consideration of whether the results from Experiment 2 could be reproduced using soils from a different site (Case Study 1), but also afforded the chance to assess what happened to the plants grown in those soils if they were subjected to differing watering regimes. For each sample, one of the pots was watered optimally, one was waterlogged and the remaining pot was subjected to drought conditions. First the optimally watered plants were examined to allow a direct comparison between plants grown in this and Experiment 2, before then moving on to consider the plants grown under droughted and waterlogged conditions, so that the significance of both nutrient status and water availability could be assessed for barley development. Case Study 1 was subject to limited trial excavation, which allowed greater volumes of soil to be used in the growth experiment, hence the ability to use three watering regimes per sample. Because of this however, it must be noted that this experimental work does not present a direct comparison between plant growth effects, crop mark formation and geophysical results as Experiment 2 did. In the latter, the soils in which the plants were grown represented a vertical sample of topsoil, feature materials and occasionally natural, essentially taking an albeit disturbed slice of the growth medium that allows the crop marks to form and provides the geophysical response. In this case soils from the individual features comprising the site were taken separately, providing information on their individual characteristics rather than the bulk soil character that is generally the subject of remotely sensed information. As described in Chapter 3, augured soils were also available from this site, however the context samples were used not only because of the larger volumes available, but also because a comparison with results from the excavated and augured samples from this site and the augured Case study 2 samples was necessary as a comparator. This then provided a logical step between these two experimental sets and the information from excavation only at Case study 3, discussed below. As will be discussed, a statistical analysis of the mean differences between the augured and excavated soil elemental compositions showed that there were no significant differences in concentrations between the two sources of soil samples, and this means that the augured and excavated soils from all of the Case Studies can be safely compared (see

page 250). As mean data for the individual features provided the most useful information in Experiment 2, this will continue to be used throughout the reporting of the experimental results, unless the per pot data is more useful for illustrative purposes. As stated in Experiment 2, the limitations of this data are recognised, and extend mainly to experimental group sizes and the problems of comparing data averaged from between 2 to 14 pots with that comprising a single pot for example. However this is felt to be the best way to present the data given the natural variability of the plants and also it allows a more direct comparison between the results of the individual components of the whole experimental work. For mean data, error bars based on relative standard deviation (percent) are provided, and show that the trends exhibited by the graphs are generally reflected in the whole dataset.

Before looking at the responses recorded in plants that were droughted or waterlogged during growth it would be useful to reconsider the kind of responses expected from features that reveal themselves as crop marks under such situations. This is summarised in Table 6.9. Because the norm is to fly mainly during good summer weather and thus, the generally financially-directed tendency to wait until these weather conditions are established, there are few conventions established for identifying crop mark responses under waterlogged conditions, although Allen does mention in passing the appearance of marks at Port Meadow, Oxford, failing to provide any more detail than the recognition of “a number of circles and other marks” appearing in the “low-lying, damp and often flooded” area (Allen 1984, 78). Wilson (2000 71, 184-5) discusses the effects of rotary-type irrigation, and land drains in relation to wet growth conditions, and also the adverse effects of the presence of pans and their associated impeded drainage relative to cut features, which effectively remove this impedance, and improved drainage results locally over such features. He cites inhibition of growth and crop failure as the main outcomes of root waterlogging, nutrient leaching and development of acidic conditions leading to denitrification. He indicates that N and Ca are important to this effect, with reduced availability of P at low pH encountered in waterlogged soils adding to reduced vigour, and also allowing positive growth over buried, mortar-rich features such as walls that provide higher Ca levels, making P locally more available. This suggests that under very wet conditions ditches and other cut features, and also masonry-constructed features such as building foundations and buried walls, will appear as positive crop marks, with interiors and probably the surrounding undisturbed ground having negative growth, assuming that there is panning below the topsoils. Although this series of experiments tend to concur with the likelihood of crop mark development under conditions of excess water (see Experiment 5) no experimental work was undertaken to examine the

response of crop plants to such features as buried masonry, although this would be a relatively easy experiment to design, and would be useful given the reporting of both positive and negative responses to such features, which appears to be predominantly dependent upon soil chemistry.

Under drought conditions, which are the norm generally when crop marks are considered, cut features are likely to appear as areas of positive growth, whilst their surroundings tend to have a lighter hue and less dense habit. Features that further reduce topsoil depths, such as stone-constructed building remains or areas of compaction such as path and roadways, make these lighter coloured, more sparse growth effects likely to be even more pronounced, with ultimately, crop failure. The comparison between expected and observed responses is made later in Section 6.5 (Table 6.20) when growth effects noted during Experiment 4 due specifically to changes in watering regime are considered.

Table 6.9: Summary of Traditionally Expected Crop Responses to Archaeological Features

<i>Feature</i>	<i>Expected Response</i>
Undisturbed ground	Average growth
Undisturbed wet ground	Negative growth
Cut features, dry weather	Positive growth
Cut features, wet weather	Positive growth
Banks, dry weather	Negative growth
Banks, wet weather	Negative/positive growth
Ca-rich masonry, dry weather	Negative growth
Ca-rich masonry, wet weather	Positive growth
Building remains/compaction, dry weather	Negative growth
Building remains/compaction, wet weather	Positive/negative growth

Assessment of Growth in Optimally Watered Plants

Beginning with germination rates, evaluation of the growth characteristics from the experiment reveal that in the optimally watered pots those growing in soil taken from the natural below the medial ditch of Case Study 1 germinated the fastest. For the soils from actual archaeological features (the bank and ditch), the bank soils provided an environment conducive to fastest germination (Figure 6.13). This is contrary to the outcome expected, but may be a response to the soil conditions at the site that caused the magnetic anomalies also to

be the reverse of that expected, and is based upon the assumption that rapid germination and initial plant density arising from this equates with positive crop mark formation. Figure 6.2b also shows lower germination rates over Case study 2 ditches.



Figure 6.13:
Mean percentage germination rates during the initial stages of Experiment 3 by feature type.

It is interesting that the natural used in this experiment was sampled from below the excavated medial ditch (Appendix 6). Normally natural, or in other words subsoil, is not thought to be conducive to satisfactory growth and would never be used as a growing medium horticulturally because it tends to lack humus and various essential plant nutrients, for example phosphorus, that are available in topsoils. However, for germination success at least this has proved not to be the case.

In Figure 6.13 the red line remaining constant at 90% represents the expected maximum germination rate based on the results of Experiment 1. Ultimately only those seeds grown in soils from the bank approach that level of germination success. Under field conditions it is possible that there may be a combined effect from the ditch and natural that would result in germination being greatest over the ditch features, as opposed to the bank. However, it is unlikely, given that the ditch in question was over 1.0 m deep (Hanson and Sharpe in prep;

Appendix 6), that this would apply to germination, although it may have an effect on nutrient and water supply for maturing crop plants, but this is discussed below.

Here, for optimally watered plants at least, the bank shows a denser growth initially, and would therefore be evident as a positive mark if these results translated into the field situation. Whether this is the case under field conditions cannot be determined as none of the available aerial photography of the site was taken at the time that the crops were germinating.

The averaged data for plant height revealed that in the optimally watered plants, the tallest growth was recorded in plants grown in topsoil (Figure 6.14), whilst of those growing in soils from archaeological features, the bank soils supported plants with the tallest growth. This developmental trend, which correlates with germination success, is completely reversed for mean numbers of tillers, with the highest numbers developing in ditch-grown soils, those grown in topsoil a close second, and the lowest number of tillers being recorded for the bank soils (Figure 6.15). The same pattern holds for the average number of leaves for the individual contexts, which in combination with the numbers of tillers would translate directly into crop density, with the highest density appearing over the ditches and the lowest over the banks. This would recreate the expected crop mark response for these features. Numbers of dead leaves are lowest for the plants grown in bank soils, but this is to be expected given the generally lower numbers of leaves and tillers produced. In the ditch- and topsoil-grown plants, however, there are lower numbers of dead leaves, with error bars for each of the contexts indicating smaller variations in numbers of dead leaves per plant than in any of the other parameters, which would enhance the positive appearance of the growth of the plants over the ditches if viewed aerially. For all of these growth characteristics, the ditch- and natural-soils produces similar responses, suggesting that they share some properties that are responsible for producing this growth

Finally, the harvested weights for the plants are shown in Figure 6.16. This shows that the bank soils produced plants with the lowest biomass, and ditch soils supported higher production rates. Not surprisingly the topsoil allowed for the largest accumulation of aerial growth in the barley plants. Again the natural-grown plants produced a similar amount of aerial growth as the ditch-grown samples. In the dried plants and with due consideration of relative standard deviations, it appears that there was little difference in weights of plants from the individual contexts, with the exception of those grown in topsoil. This illustrates

the importance of water content for plant growth characteristics that did vary significantly with context, such as leaf area, and indicates that water availability is as much a function of individual soil characteristics as it is of supply, all plants receiving standardized volumes of water despite the variations in biomass clearly exhibited in the wet weights in Figure 6.16.

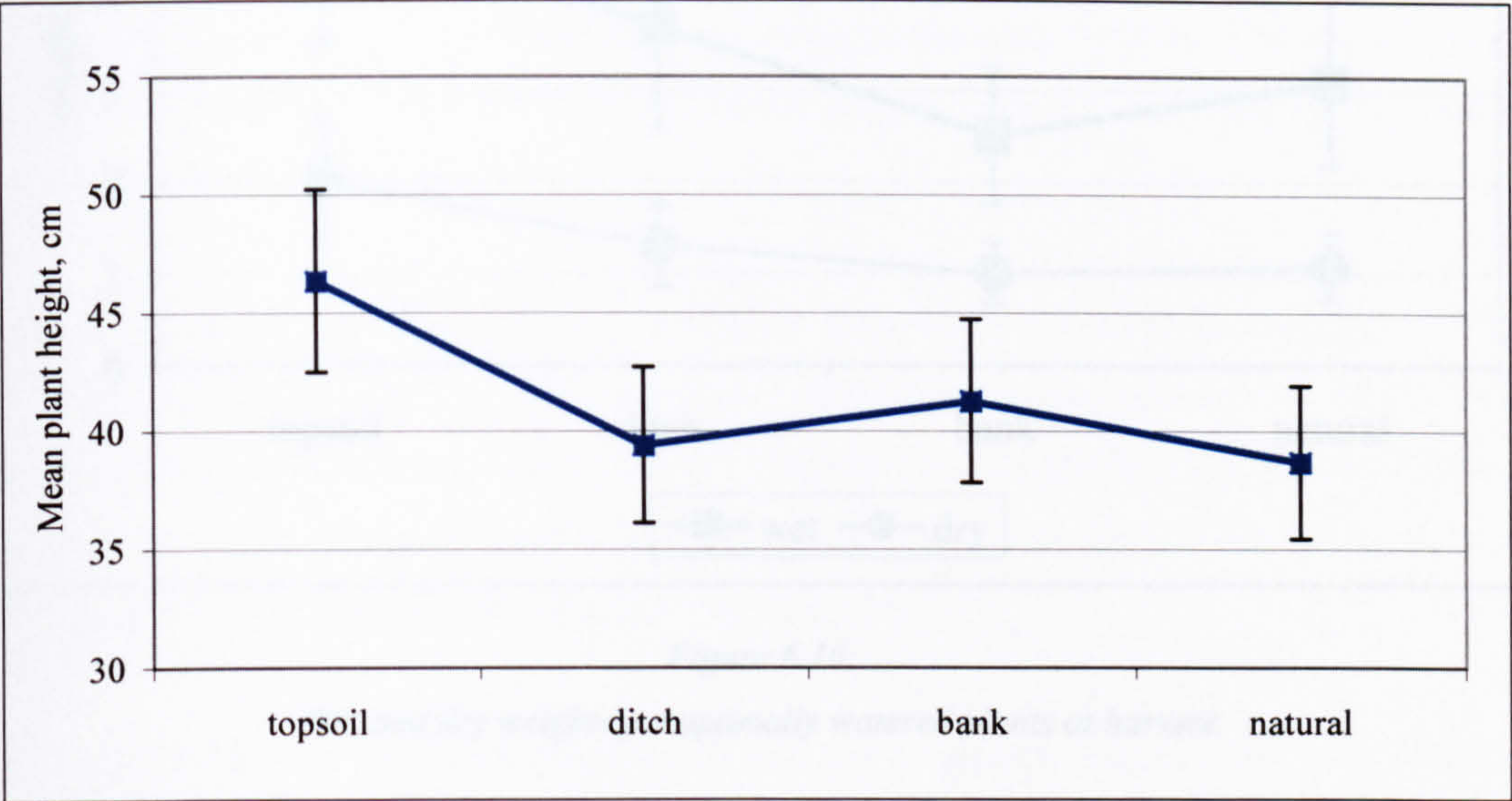


Figure 6.14:
Mean heights of plants watered optimally and grown in soils from different contexts from Case Study 1.

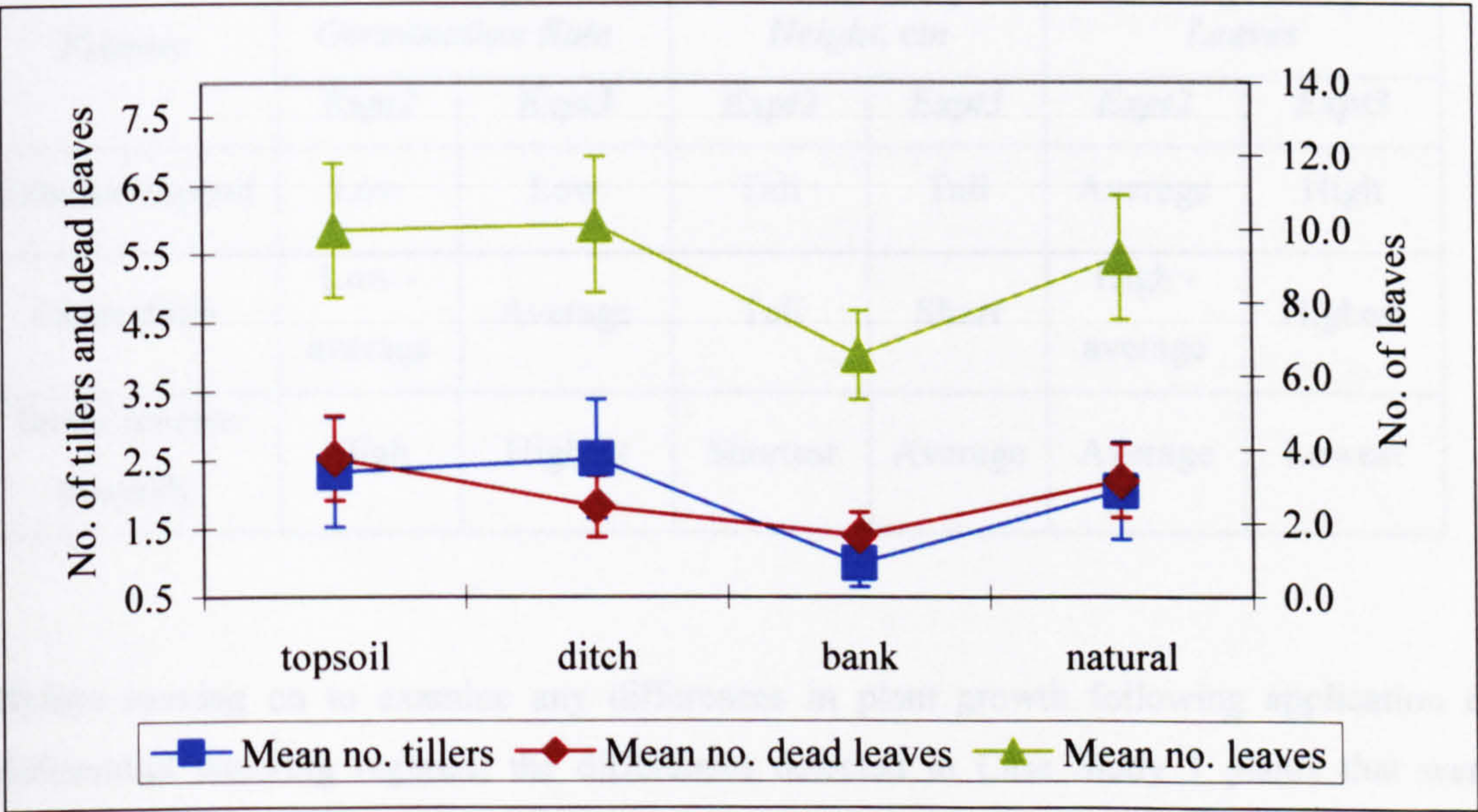


Figure 6.15:
Average numbers of leaves, tillers and dead leaves for the optimally watered individual contexts at Case Study 1.

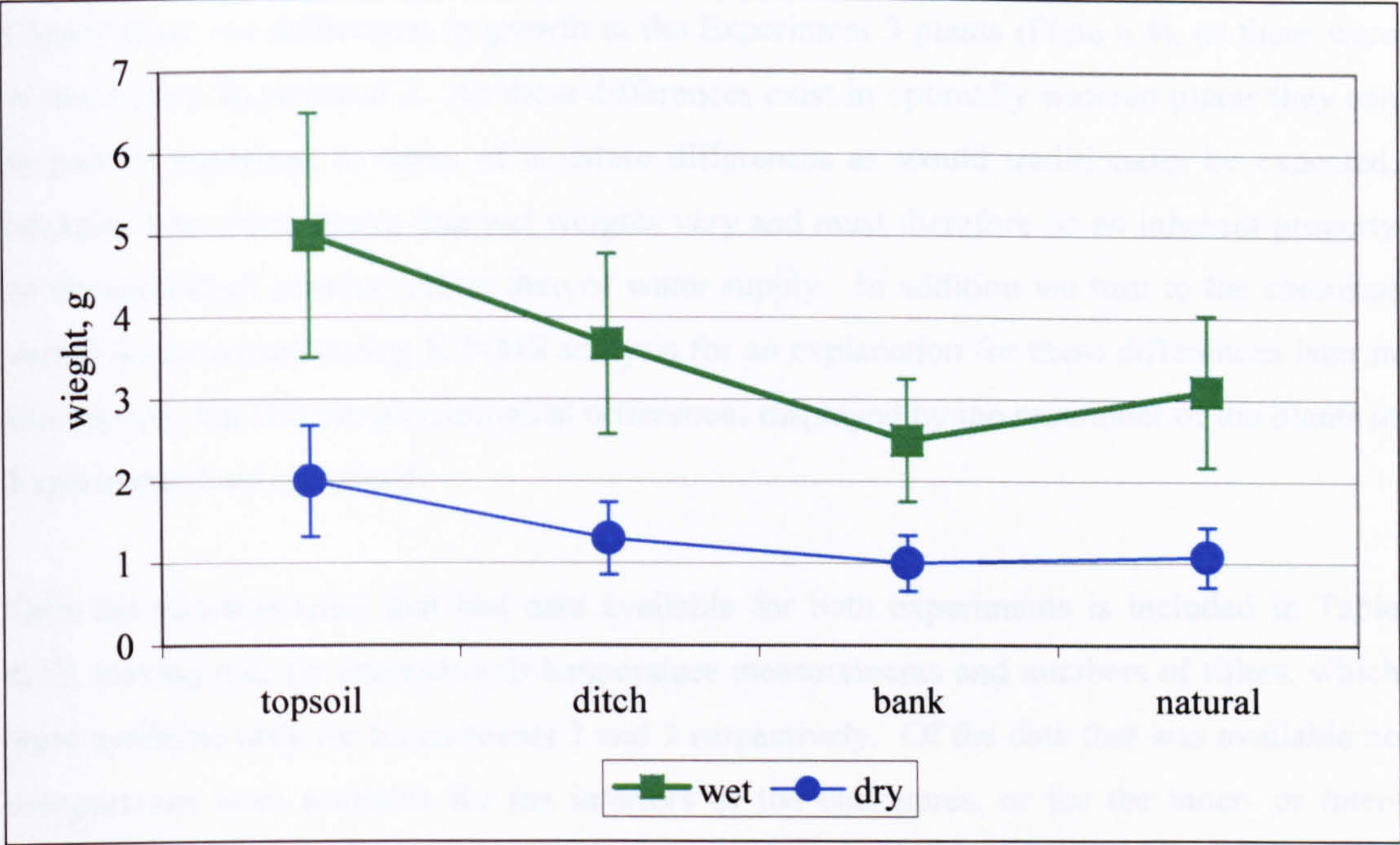


Figure 6.16:
Wet and dry weights for optimally watered plants at harvest.

Table 6.10: A Comparison of Optimally Watered Plant Growth Responses Recorded During Experiments 2 and 3

Feature	Average Germination Rate		Average Leaf Height, cm		Average No of Leaves	
	Expt2	Expt3	Expt2	Expt3	Expt2	Expt3
Exterior/ topsoil	Low	Low	Tall	Tall	Average	High
Outer ditch	Low - average	Average	Tall	Short	High - average	Highest
Bank/ reverse anomaly	High	Highest	Shortest	Average	Average	Lowest

Before moving on to examine any differences in plant growth following application of differential watering regimes, the differences detected in Case Study 1 plants that were optimally watered from the four different contexts are summarised in Table 6.10, compared to those identified in plants from Case study 2 (Experiment 2).

Clearly there are differences in growth in the Experiment 3 plants (Plate 6.4), as there were in those from Experiment 2. As these differences exist in optimally watered plants they can in part be explained in terms of moisture differences as would traditionally be expected, because it has been shown that wet weights vary and must therefore be an inherent property of the individual contexts rather than of water supply. In addition we turn to the chemical variations measured during ICP-MS analysis for an explanation for these differences later in this section, but first the physiological differences displayed by the remainder of the plants in Experiment 3 are examined.

Only the characteristics that had data available for both experiments is included in Table 6.10, leaving out, for example soil temperature measurements and numbers of tillers, which were available only for Experiments 2 and 3 respectively. Of the data that was available no comparisons were available for the interiors of the enclosures, or for the inner- or inter-ditches and so again these were excluded from the table.

Although there was no direct comparison for the enclosure exterior for Case Study 2 (Experiment 2) it was decided to compare this to data for topsoil at Case study 1 (Experiment 3) as both are effectively the undisturbed natural media present at these sites. For the remaining data it can be seen that there were some correlations between growth responses. Germination rates were similar for the features at both sites, although leaf heights and numbers did not correlate as closely, with the undisturbed areas and ditches at the two sites exhibiting the most similarities in growth characteristics. This is to be expected given the much more loosely postulated presence of the bank at Case Study 2 (based upon interpretation of geophysical responses), with no further evidence offered by these results.

Plate 6.4 indicates that the differences measured were also visible in the growth habits of the individual plants. Ignoring the control plants it can be seen that those remaining exhibit taller growth when sown into ditch soils.



Plate 6.4:

Optimally watered plants at harvest, with from left to right: plants grown in compost (control); topsoil; natural; inner ditch; natural and inner ditch, a)during growth and b) at harvest ,from Trench 1, Case Study 1 Comparison of plants grown during Experiment 3 under differing watering regimes.

Figure 6.17 shows the graphs of average germination rates over the space of 2 weeks for the individual watering regimes. For the waterlogged (b) and droughted (c) plants percentage germination barely tops 90%, which is the figure expected under optimum conditions based on Experiment 1. All percentage germination rates below this figure can be ascribed to cultural conditions. Thus even in the optimally watered plants, germination of all but those growing in the bank soils have been adversely affected by cultural conditions.

In the waterlogged plants percentage germination rates were highest for the ditch soils. In those pots that were droughted the percentage germination for the control pot (not shown in Figure 6.15c) dropped significantly in week 2, indicating that moisture stress was affecting those plants that were experiencing drought conditions. Here, as in the optimally watered plants, germination rates were highest for plants grown in soils comprising the enclosure bank. Clearly then, water availability does have an effect on germination.

Figure 6.18 shows the maximum heights to which the plants from the different contexts had grown on average by 6 June 2000. There is an inverse relationship between growth patterns in the bank and ditch soils for optimally watered and water-stressed groups. Optimally watered plants produced a significantly taller growth range in the ditch soils compared to the bank and other soils, which was the expected response based upon crop mark development in the field. Conversely, both waterlogged and droughted plants developed taller growth on bank soils rather than those taken from the ditch, with overall growth in droughted plants tending to be taller than waterlogged ones, except for those grown in the natural. Conventionally this is not what would be expected, as under drought conditions the ditch environment, would be expected to produce accelerated growth. However, this may be a consequence of basing the experimental work on pot growth rather than using field observations, as the main reason that positive growth is thought to develop over ditches is the additional depth of soil generally present and its resulting reservoir effect, which was discussed in Chapter 2. However, it is not sufficient to dismiss this result simply on the basis that it is not a field observation. It is clear that soil from the same context produces differing growth responses when water availability within that soil is altered (see for example Plate 6.5), which is the basis upon which crop mark formation mechanisms are explained at present. The changing response *within* watering regime to the different contexts, however, does suggest that there is something more than water availability that is responsible for these growth differences. Additionally there is the depth factor to consider, which is addressed in

Experiment 5. Full discussion of the growth characteristics described here though must clearly wait for the results of ICP-MS analysis.

Heights were measured again when the plants were harvested, and Figure 6.19 shows the averaged heights for the individual contexts at this time. The plants that were droughted during the experiment had produced the shortest growth by this stage. This decreased height was most marked in those droughted plants grown in bank soils. Waterlogged and optimally watered plant height ranges were similar for the individual contexts, tending to confirm the important role of water in cell elongation and therefore extensional growth.

Again, differences *within* water treatments suggest more factors than water availability are involved in producing growth differentials, with the only variables possible under controlled glasshouse conditions being some factor associated with soil composition. However, the variations noted within the individual contexts between watering groups confirm that water availability remains a factor.

When considering the average numbers of leaves produced per plant by feature (Figure 6.20), the optimally watered and waterlogged plants again produced denser growth in the ditch soils than in those taken from the bank, and conversely the droughted plants produced higher numbers of leaves in the bank than in the ditch soils. Leaf production for the waterlogged and optimally watered plants was very similar for each context, suggesting that of the water stress treatments droughting has the biggest effect on growth.

At harvest the numbers of dead leaves were averaged for each context revealing that the optimally watered and waterlogged plants produced similar quantities, following approximately the trend in numbers of living leaves, and thus reflecting the numbers of leaves produced in total (Figure 6.21). In the droughted plants for all soil samples except the topsoil there were higher numbers of dead leaves present compared to the plants from the other watering regimes, and this was most pronounced for the bank soils. This suggests that the higher numbers of leaves produced in the droughted plants over the bank may be a stress survival response where leaf death is compensated for by higher production, and translated into field terms the high number of dead leaves present are likely to reveal the bank as a negative crop mark feature, as would be expected.

The average numbers of tillers produced by the plants grown in soils from the various contexts produced what was to become a familiar pattern in the experimental results (Figure 6.22). Waterlogged and optimally watered plants produce the highest number of tillers over the ditch soils compared to the banks, and the situation is reversed for the droughted plants, tending to confirm that this is a response to reduced water availability.

Finally, the harvest weights for the plants from the individual contexts were noted and are produced as graphs in Figure 6.23, with a) representing the wet weights and b) the weights of the plant material once it had been oven dried. All three watering regimes follow the same trend, with weights being highest in those plants grown in topsoil samples, followed by those grown in ditch- and natural-soils respectively. Those plants grown in the bank soils accumulated the lowest biomass weights for all watering regimes. The waterlogged plants had the highest wet weights except for in bank-grown soils, and the droughted weights were consistently lowest. Once dried the droughted weights were still lower than those recorded in plants from the other two watering regimes. This is clearly related to water-availability driven uptake within the plants. Droughting inhibits leaf elongation rates and reduces cell turgor leading to a decrease in leaf area and retardation or cessation of shoot growth (Marschner 1995, 186; 532; 535), and this translates into a plant's ability to accumulate biomass and thus increase in size adequately. The results of ICP-MS analysis of these experimentally grown plants, presented below, helped to determine whether this effect also extends to nutrient uptake, as was suspected. Table 6.11 summarises the growth differences detailed for Experiment 2 before moving on to examine the chemical differences measured during ICP-MS analysis of the soils and plants used during this examination. As well as the excavated soils a selection of augured soils were also analysed and the results are included below.



a) Inner ditch



b) Natural



c) Outer edge of medial ditch

Plate 6.5:

Visual appearance of plants from the same contexts subject to different watering regimes. From left to right in all cases plants are droughted, optimally watered and waterlogged

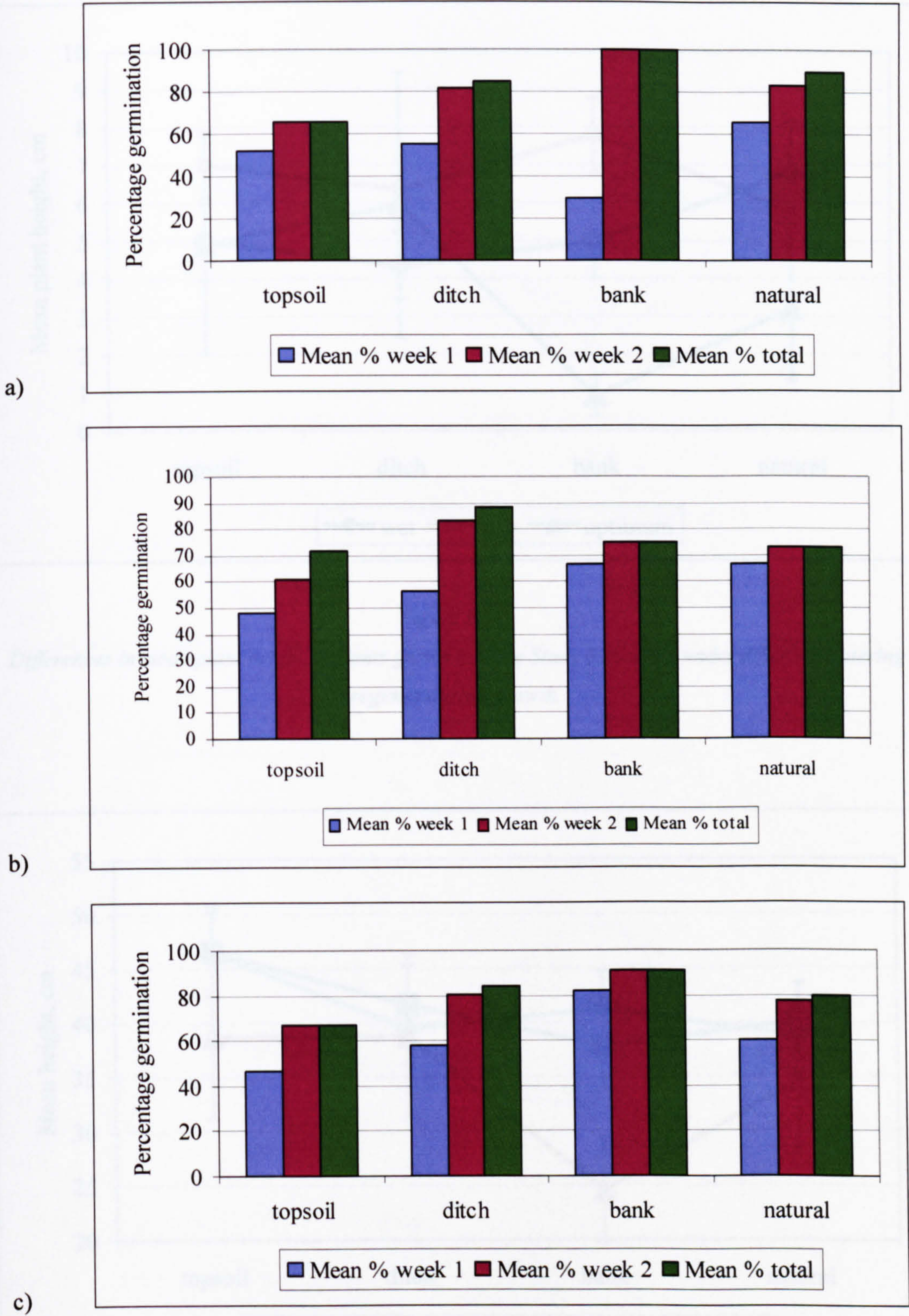


Figure 6.17:
Averaged percentage germination rates in plants grown in contexts from Case Study 1 for a) optimally watered plants; b) waterlogged plants and c) droughted plants.

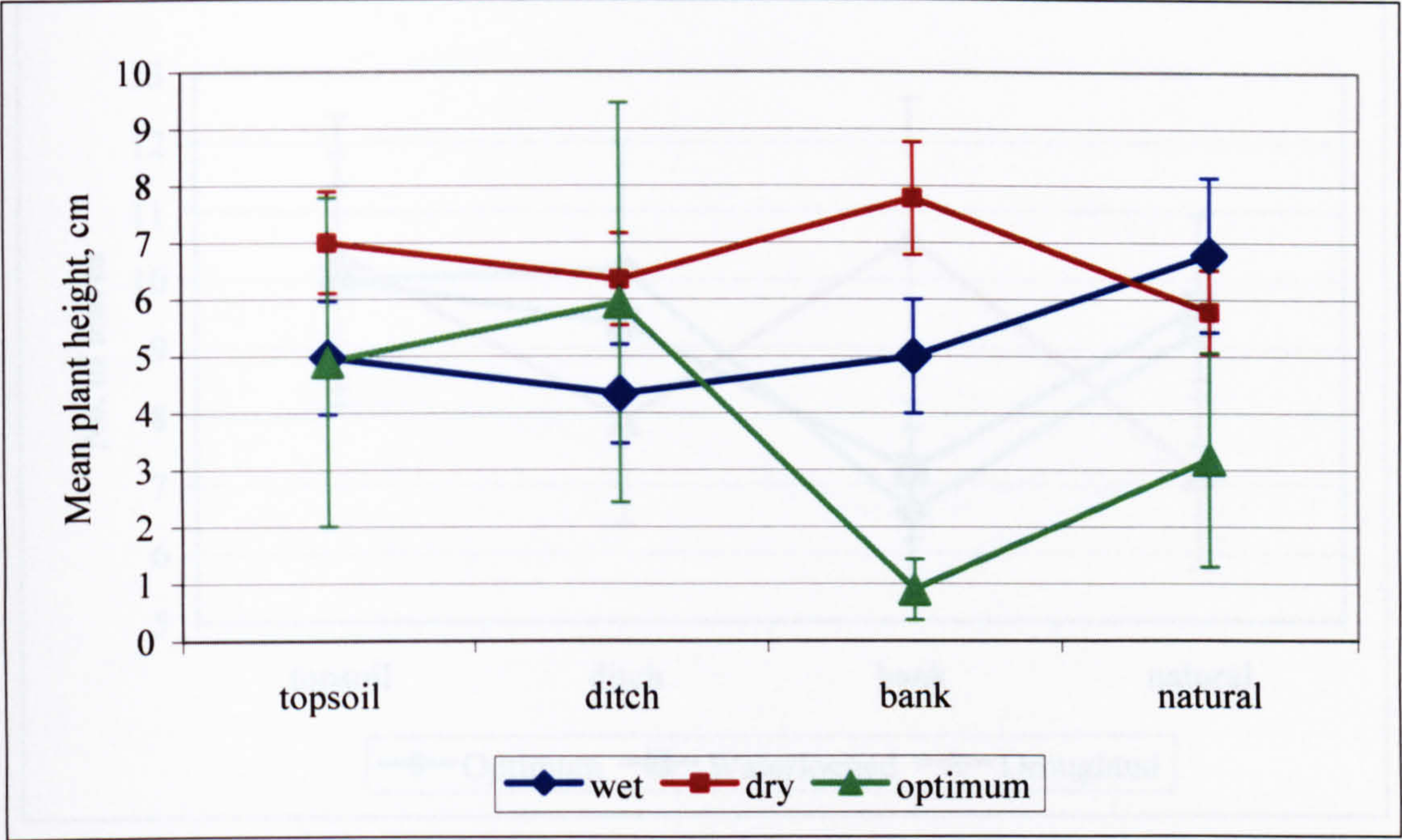


Figure 6.18:
Differences in mean plant height of plants grown in Case Study 1 contexts under differing watering regimes during growth.

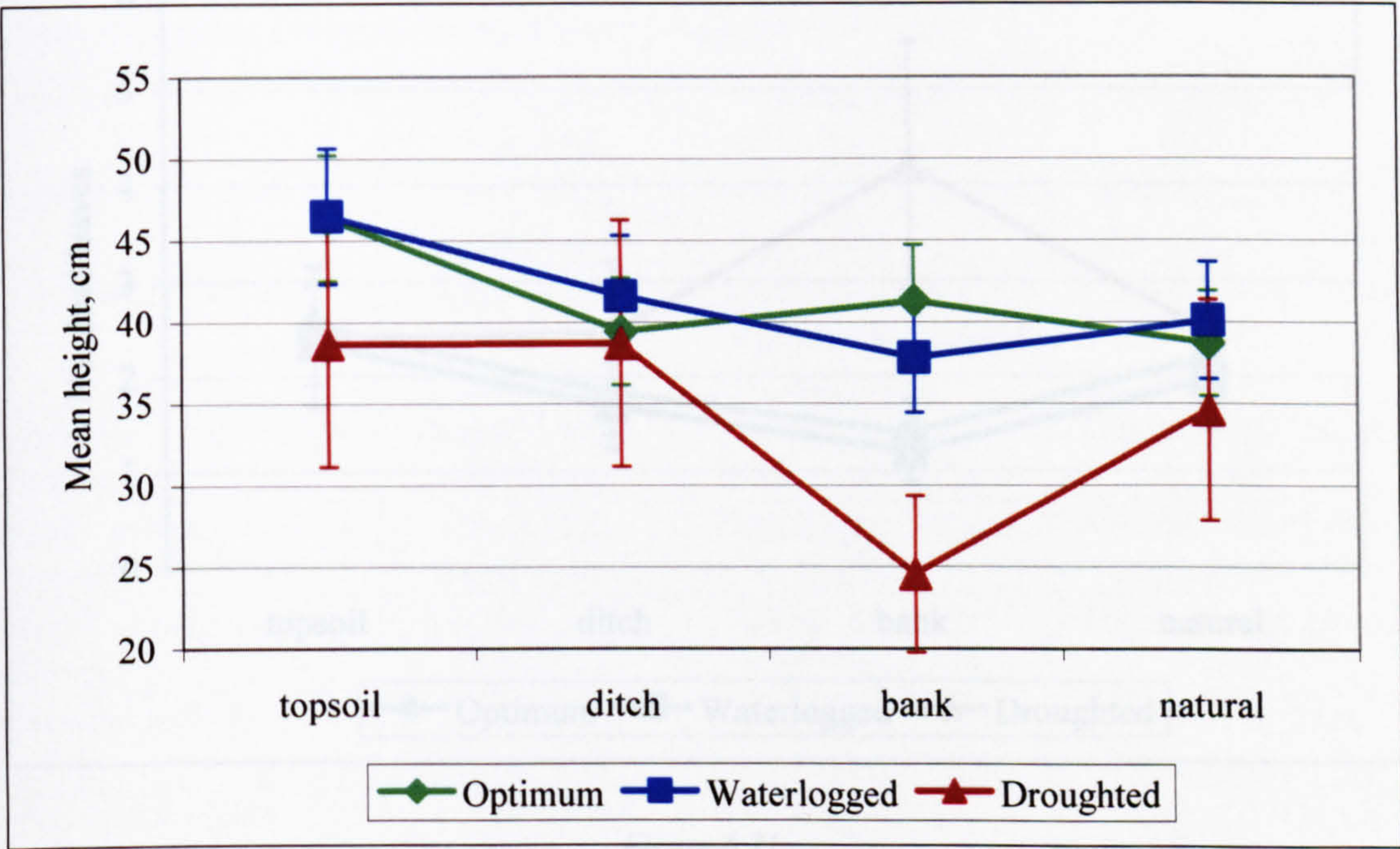


Figure 6.19:
Maximum mean heights of plants grown in different contexts at harvest.

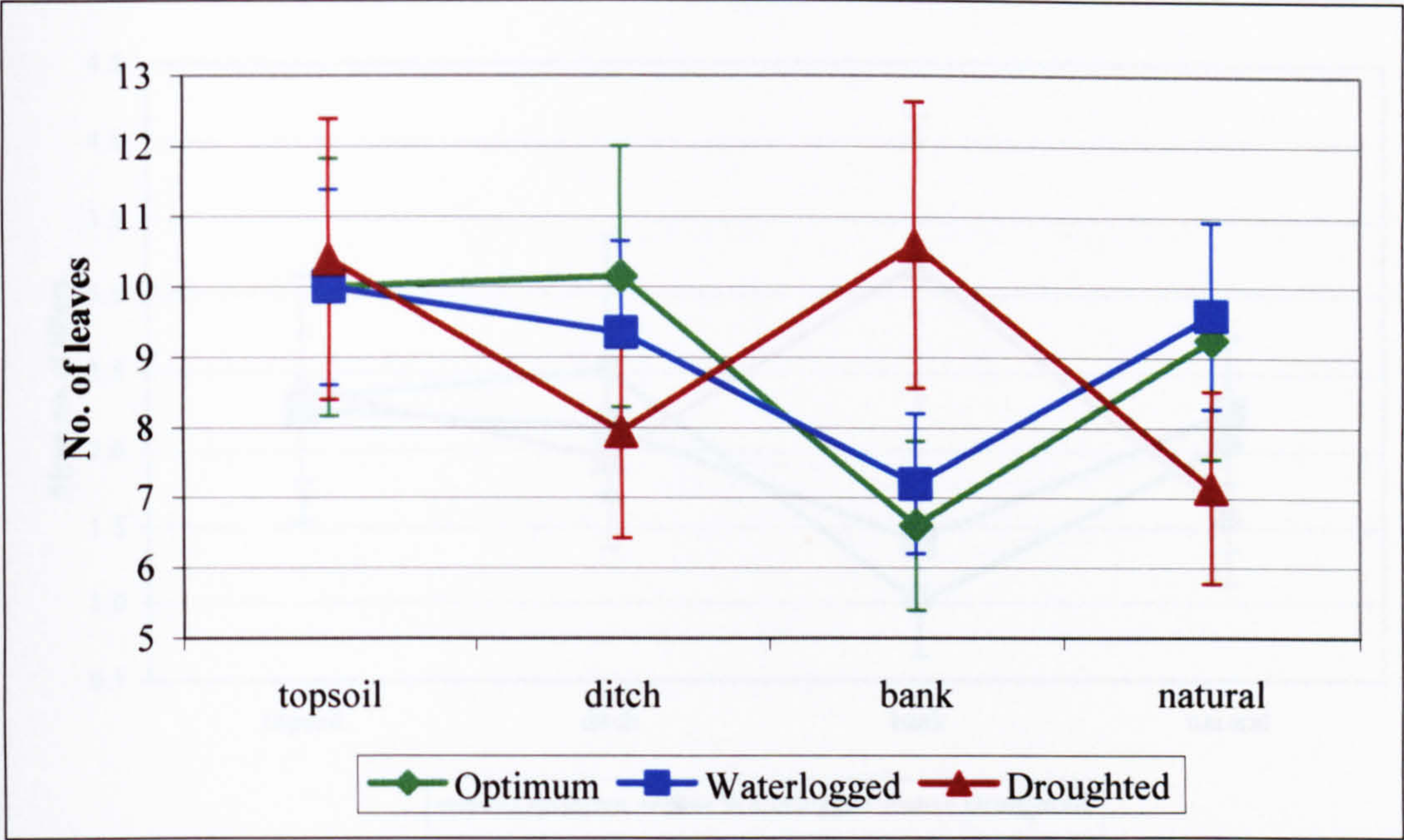


Figure 6.20:
Mean numbers of leaves in plants grown under different watering regimes in Case Study 1 contexts.

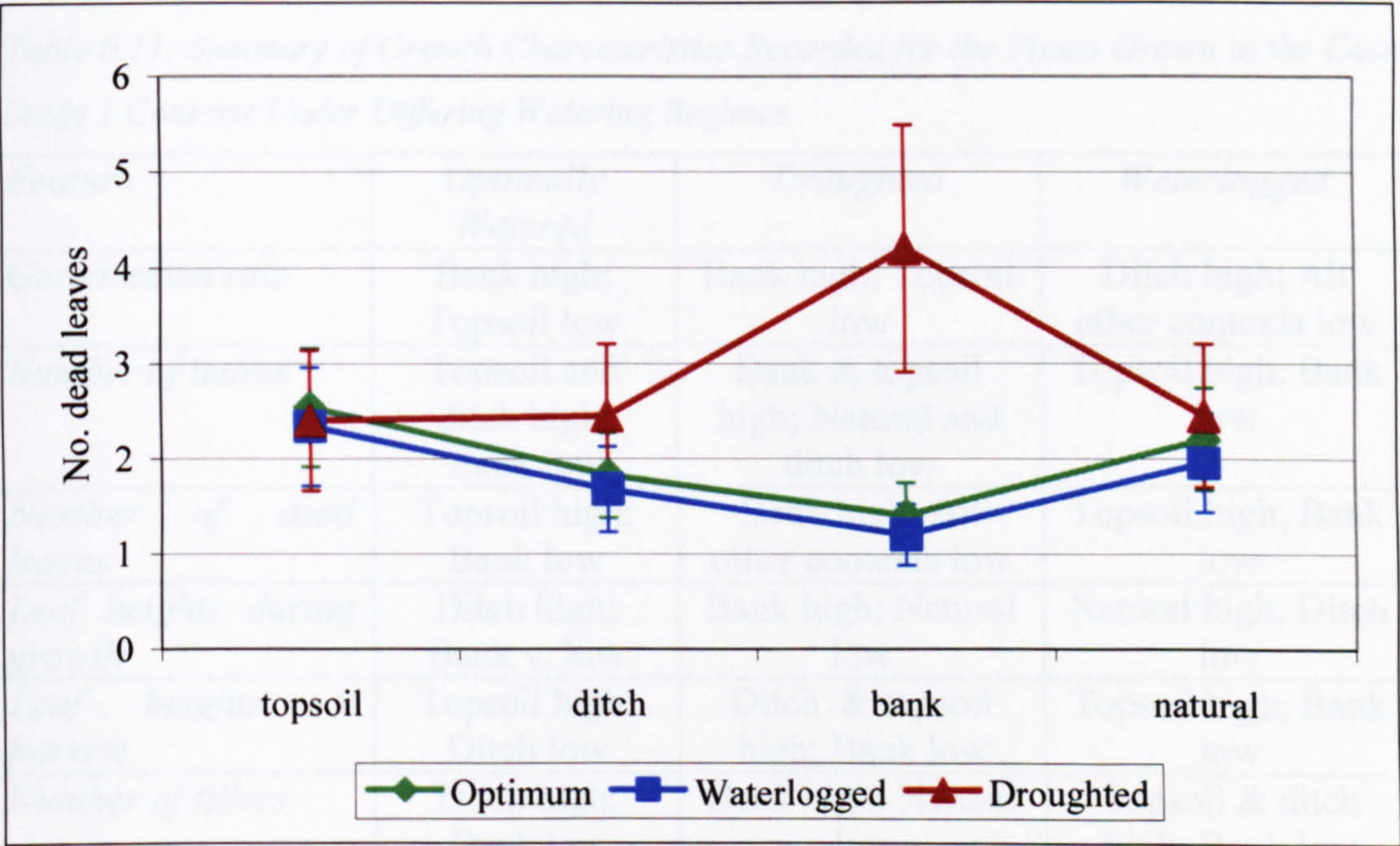


Figure 6.21:
Numbers of dead leaves averaged for features type, for the different watering regimes.

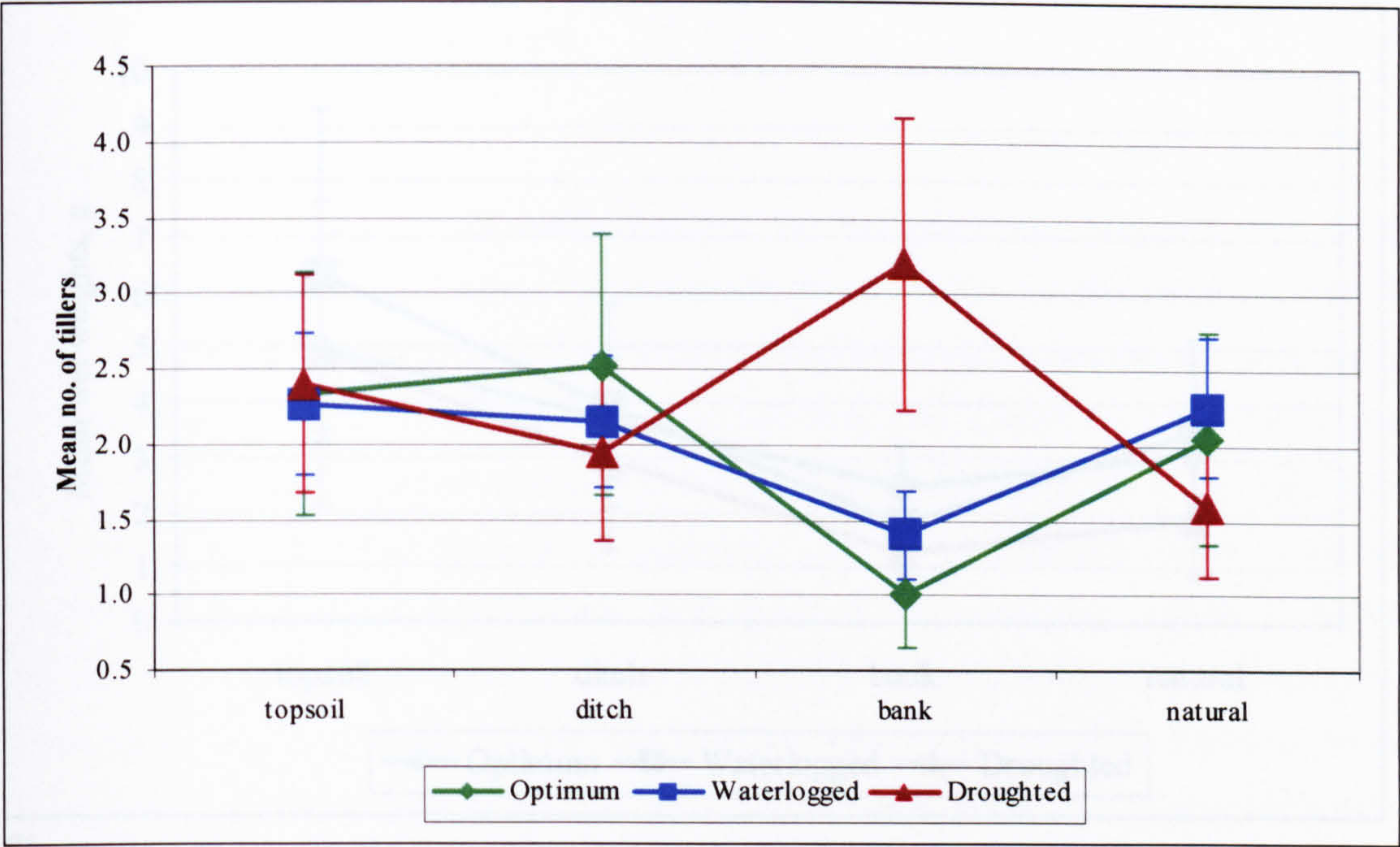
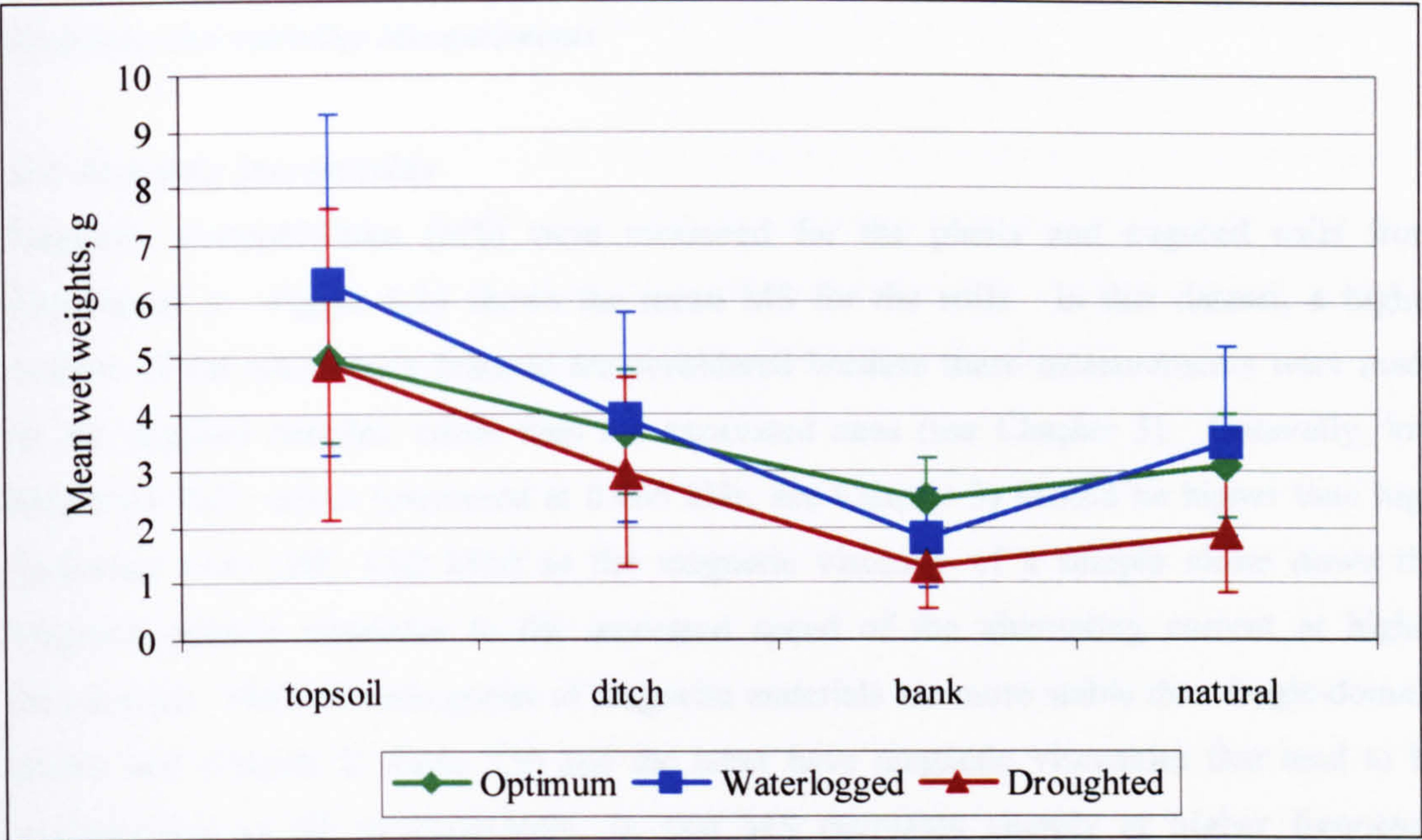


Figure 6.22:

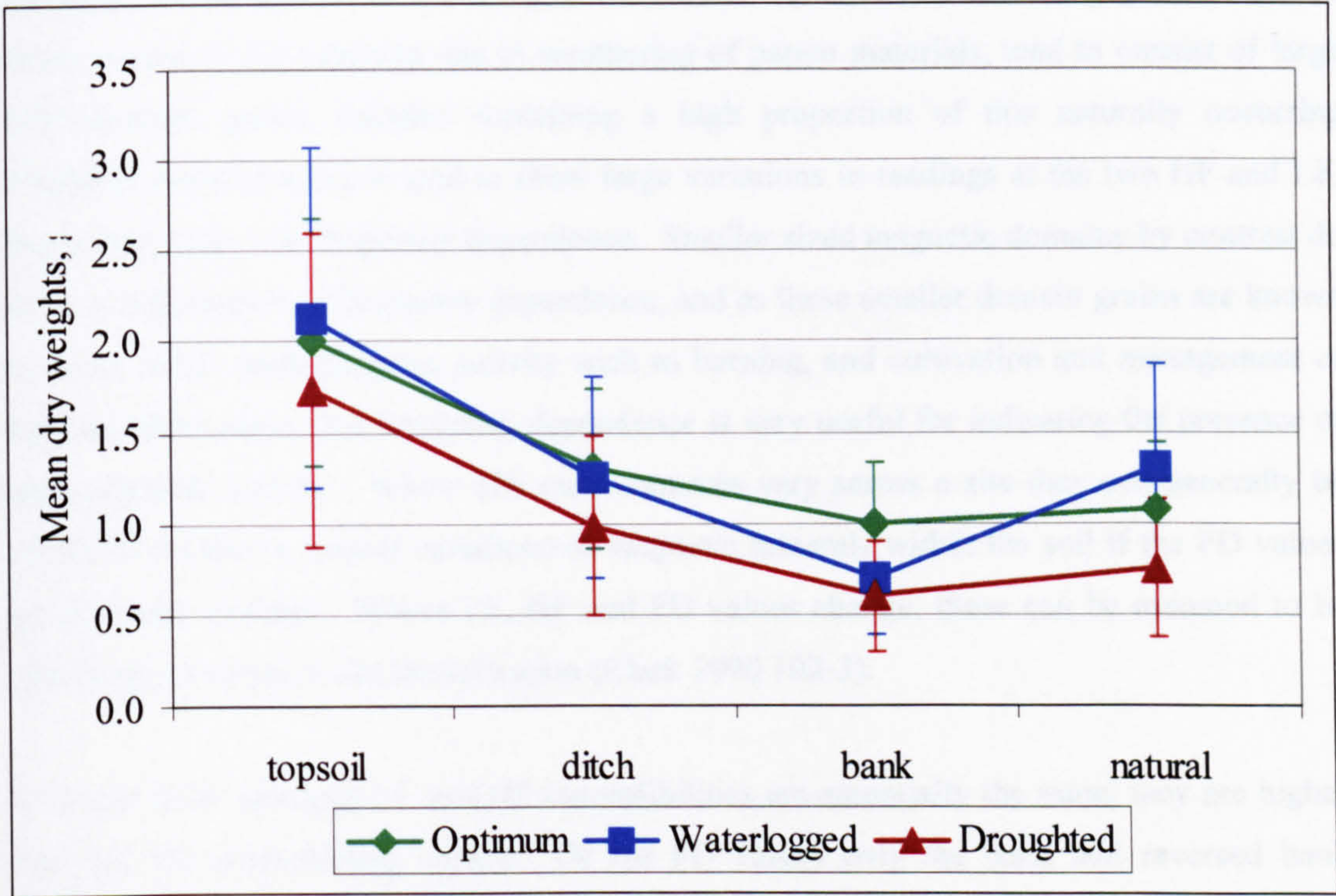
Tillering in the different contexts and differing watering regimes.

Table 6.11: Summary of Growth Characteristics Recorded for the Plants Grown in the Case Study 1 Contexts Under Differing Watering Regimes

Feature	Optimally Watered	Droughted	Waterlogged
Germination rate	Bank high; Topsoil low	Bank high; Topsoil low	Ditch high; All other contexts low
Number of leaves	Topsoil and ditch high; Bank low	Bank & topsoil high; Natural and ditch low	Topsoil high; Bank low
Number of dead leaves	Topsoil high; Bank low	Bank high; All other contexts low	Topsoil high; Bank low
Leaf heights during growth	Ditch high; Bank v. low	Bank high; Natural low	Natural high; Ditch low
Leaf heights at harvest	Topsoil high; Ditch low	Ditch & topsoil high; Bank low	Topsoil high; Bank low
Number of tillers	Ditch high; Bank low	Bank high; Natural low	Topsoil & ditch high; Bank low
Harvest weights	Topsoil high Bank low	Topsoil high Bank low	Topsoil high Bank low



a)



b)

Figure 6.23:
Mean plant weights at harvest for the various plant groups; a) wet weights; b) dry weights.

Magnetic Susceptibility Measurements

Soil Magnetic Susceptibility

Magnetic susceptibilities (MS) were measured for the plants and augured soils from Experiment 3. Figure 6.24 shows the mean MS for the soils. In this dataset, a higher number of the enclosure's features are considered because these measurements were made on the augured samples, rather than the excavated ones (see Chapter 3). Generally, low frequency (LF) values (measured at 0.465 kHz, see Chapter 3) should be higher than high frequency ones (HF, 4.62 kHz) as the magnetic viscosity of a sample slows down the magnetic grain's responses to the increased speed of the alternating current at higher frequencies. Multi-domain grains of magnetic materials are more stable than single-domain grains (see Chapter 2, Table 2.9) and the latter have magnetic viscosities that tend to be unresponsive to HF measurements, so that MS decreases sharply at higher frequency measurements. This allows the dual frequency measurements to be used to assess the type of magnetic grains present in the samples measured. As naturally occurring grains, such as those carried in the substrata due to weathering of parent materials, tend to consist of large multi-domain grains, samples containing a high proportion of this naturally occurring magnetic material will not tend to show large variations in readings at the two HF and LF, that is they have low frequency dependence. Smaller sized magnetic domains by contrast do show a high degree of frequency dependence, and as these smaller domain grains are known to occur where anthropogenic activity such as burning, and cultivation and management of soil has taken place, this frequency dependence is very useful for indicating the presence of anthropogenic activity. Where MS measurements vary across a site they can generally be shown to be due to natural variations of magnetic minerals within the soil if the FD values are low and constant. Where LF, HF and FD values change, these can be assumed to be significant in terms of site identification (Clark 1990 102-3).

In Figure 6.24, although LF and HF susceptibilities are essentially the same, they are higher than the FD susceptibility values. Of the FD values only the bank and reversed bank anomaly samples are positive, and all of the values for these features are the highest measured. In all three datasets the samples taken over the enclosure entrance are the lowest although taking the ranges of readings for these, and the samples gathered from the enclosure exterior, the error bars suggest that there is a significant probability that these reading ranges are statistically the same. The ditch samples possess the next lowest values. The interior samples have values intermediate between the ditch and bank for all measurements.

This dataset indicates that the iron minerals present at the site are largely diamagnetic in nature, based upon the negative FD values. The change to positive values over the bank and reversed bank anomaly suggests that here a paramagnetic component dominates. Linking this to geophysical responses, it helps to explain the reversed magnetic anomalies recorded at this site, with positive magnetic responses existing over the bank of the enclosure, although it does not explain why the reversed anomaly has such characteristics, given that the MS values increase when measured at LF and HF. This suggests that magnetic responses detected with the FM36 must correlate most closely with FD values. According to Table 2.9 (Chapter 2) the results suggest elemental differences in the soils comprising these different features based upon the recorded MS values. Although the correlation of LF with HF values and therefore the low FD of these samples also suggests that the variations are likely to be largely natural, suggesting a pedogenic or soil chemical origin for the differences. Table 6.12 indicates the expected significant elemental contributions to the MS values measured in soils from the various features. These will be examined in more detail during the discussion of the elemental analyses below. A statistical examination of the differences between the means of the MS values suggests that there are significant differences in the Low Frequency data, indicating that differences in Fe chemistry are present in the individual features (Appendix 7).

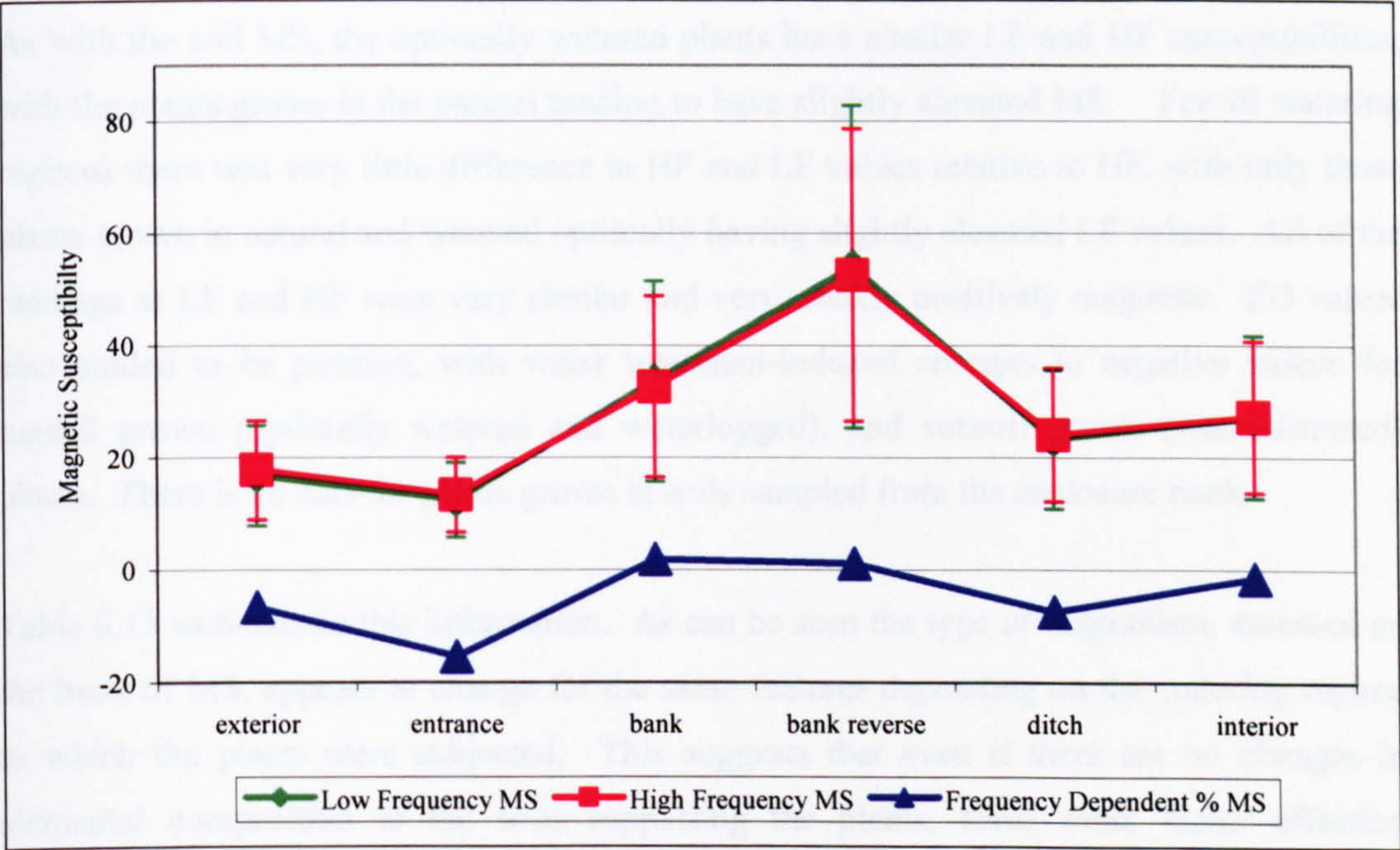


Figure 6.24:
Mean MS data for the augured soils.

Table 6.12: Significant Elemental Inputs Suggested by MS Values for the Various Case Study 1 Features

<i>Feature</i>	<i>Probable Dominant Type of Magnetism</i>	<i>Typical Elements and Minerals</i>
Entrance	Diamagnetic	Cu, magnetite, maghaemite
Bank	Paramagnetic; ferrimagnetic	Oxygen, Ti
Ditch	Diamagnetic	Cu, magnetite, maghaemite
Interior	Diamagnetic	Cu, magnetite, maghaemite

Plant Magnetic Susceptibilities

Because MS is known to be affected by the redox potential of particularly iron minerals, the mean figures for the plant MS measurements are shown separately for those plants that were optimally watered, waterlogged and droughted, as water status is also thought to affect iron mineral redox states. The graphs for these results indicate that the natural tended to have higher LF and HF susceptibilities in most cases, which is not the expected result as MS generally tends to decrease with depth (Figure 6.25).

As with the soil MS, the optimally watered plants have similar LF and HF susceptibilities, with the plants grown in the natural tending to have slightly elevated MS. For all watering regimes there was very little difference in HF and LF values relative to HF, with only those plants grown in natural and watered optimally having slightly elevated LF values. All of the readings at LF and HF were very similar and very weakly positively magnetic. FD values also tended to be positive, with water treatment-induced changes to negative values for topsoil grown (optimally watered and waterlogged), and subsoil grown (water-stressed) plants. There is no data for plants grown in soils sampled from the enclosure bank.

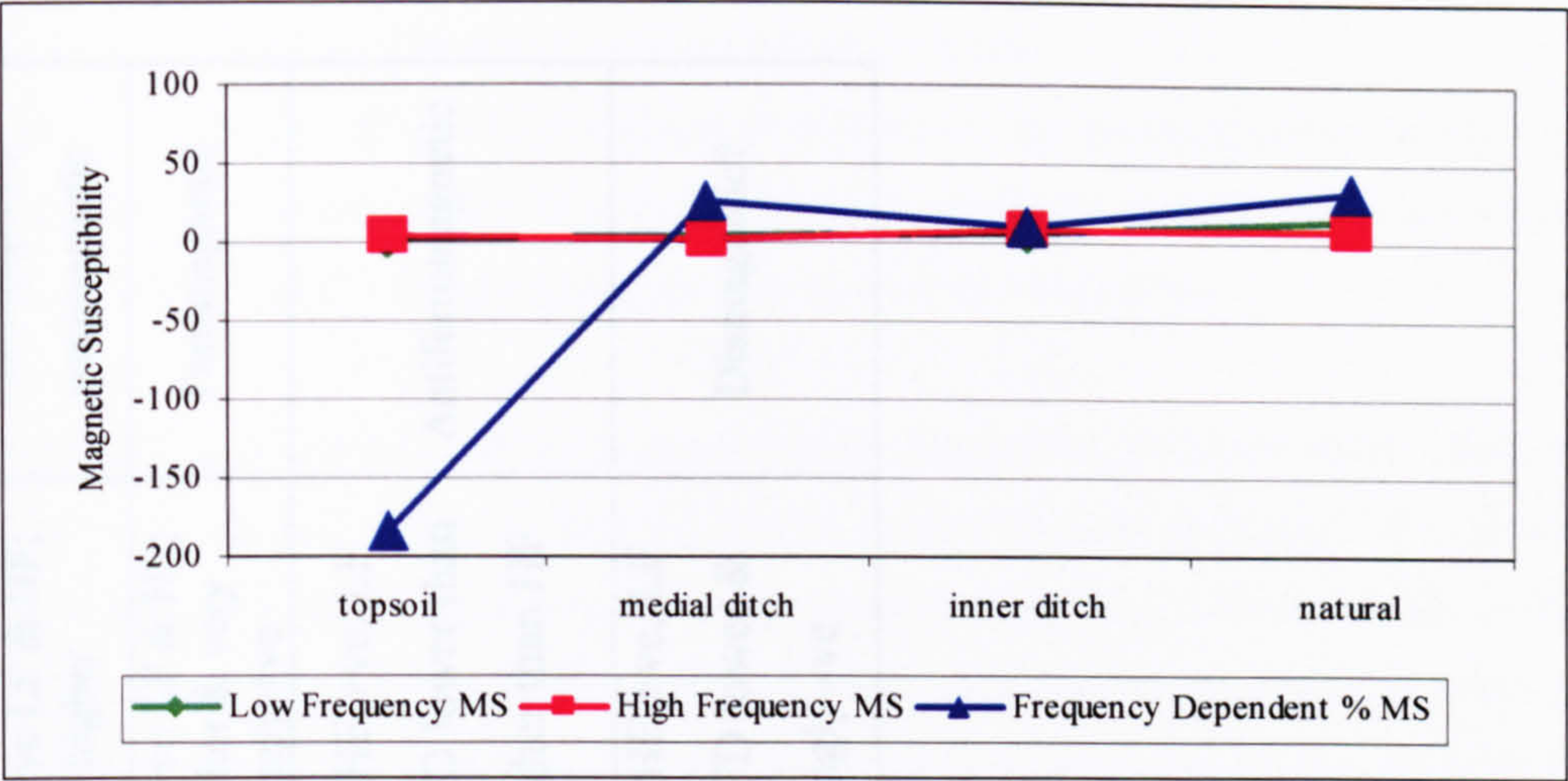
Table 6.13 summarises this information. As can be seen the type of magnetism, assessed on the basis of MS, appears to change for the same features depending on the watering regime to which the plants were subjected. This suggests that even if there are no changes in elemental composition in the soils supporting the plants, some other factor affecting elemental availability must have changed. Of the elements that cause MS changes, specifically the metal ions, Table 2.9 highlights Cu, Ti, Fe, Co and Ni compounds or ions. If the elemental analyses of the soils indicate that the concentrations of these elements are the

same, then the altered MS measured in the samples must be due to preferential uptake due not to compositional changes but to redox changes which are known to affect the ability of barley to take up the elements, particularly Fe (W. Fricke pers comm.)

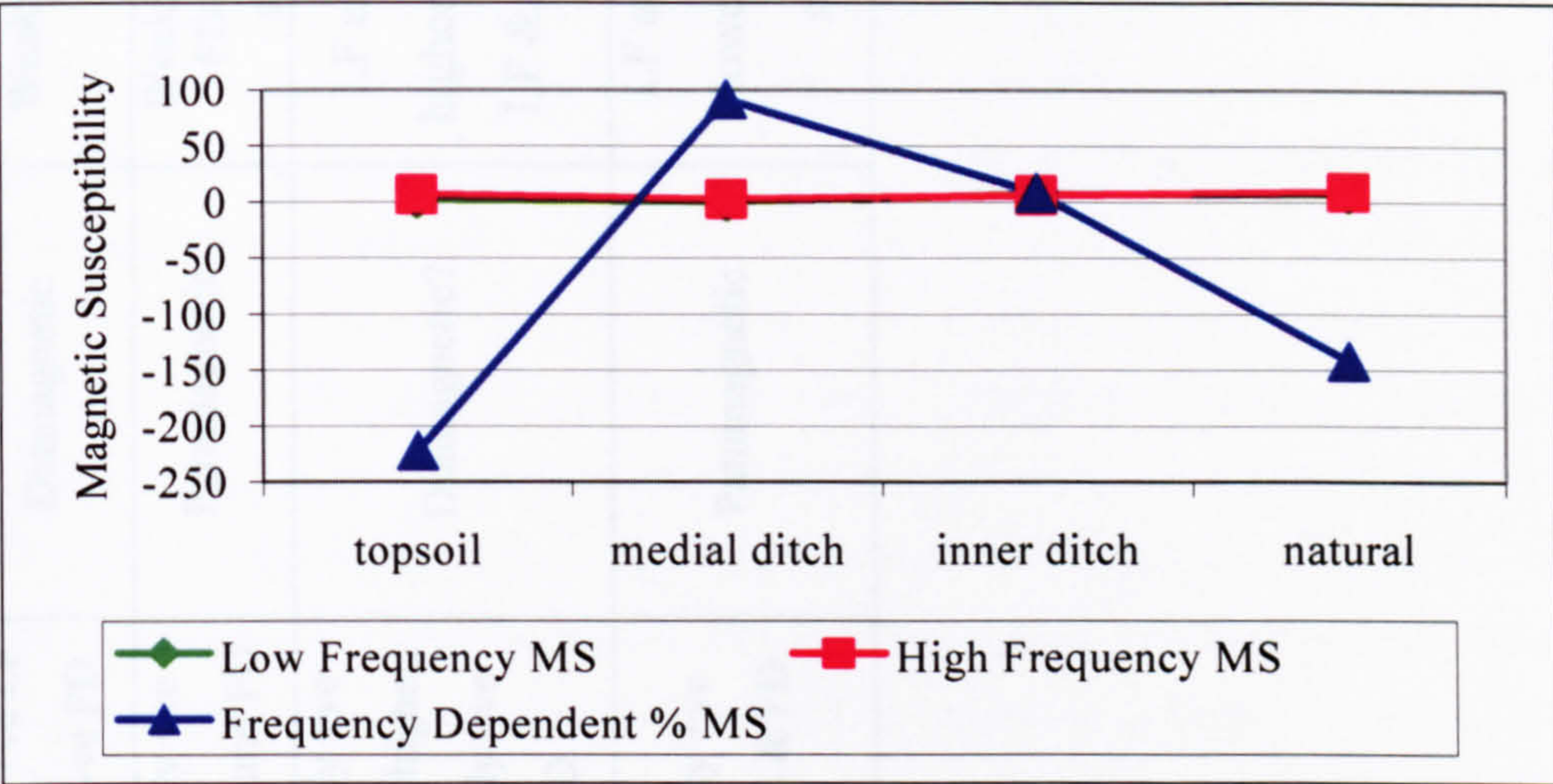
The MS values for the plants show that changes in watering regime affect plants grown in the ditch soils the most. Under all watering regimes the plants grown in natural soils produced unexpectedly elevated values, albeit subtle increases. The topsoil susceptibilities, generally expected to be amongst the highest were consistently low. Clearly this site is unusual in that MS does not decrease with depth as would be expected, but is in general increased in samples that are stratigraphically lower. This does tend to explain the reversal of the magnetic anomalies for the banks and ditches, although the crop marks and resistivity responses are as would be expected for the features, which have been confirmed by excavation (Hanson and Sharpe in prep). The MS results suggest that the cause of this discrepancy lies with the iron chemistry at the site. Perhaps there are other elemental changes that may also shed light on the results of the MS analysis and the magnetic responses. These are considered next.

Statistically, the differences between the mean magnetic susceptibilities examined on the basis of watering treatment are not so significantly different that they could not have arisen by chance. When examined by feature however, the LF susceptibilities particularly display significant differences between the means.

a)



b)



c)

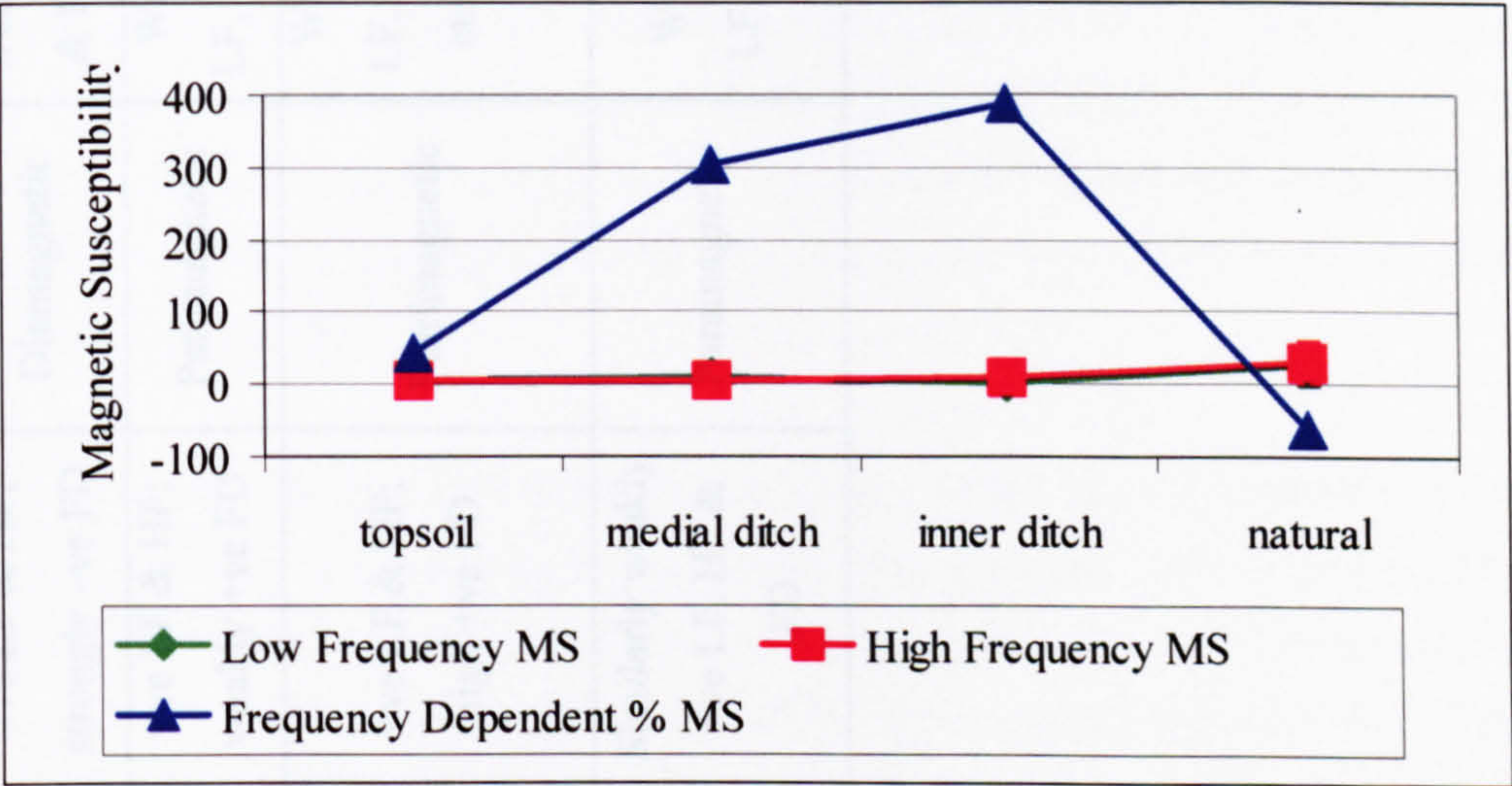


Figure 6.25:
MS values for a) optimally watered; b) waterlogged and c) droughted plants.

Table 6.13: MS Values for the Plant Samples Under Differential Watering Regimes

Feature	Optimal watering		Waterlogged		Droughted	
	MS	Magnetism	MS	Magnetism	MS	Magnetism
Topsoil	+ve LF & HF; strongly -ve FD	Diamagnetic	Weakly +ve LF & HF; -ve FD	Diamagnetic	Weakly +ve LF & HF; FD higher	Ferrimagnetic/ paramagnetic
Ditch	+ve LF & HF; weakly +ve FD	Paramagnetic	Weakly +ve LF, HF and FD	Paramagnetic	Weakly +ve LF & HF; FD higher & very strongly +ve	Ferrimagnetic
Bank	+ve LF & HF; high +ve FD	Ferrimagnetic	Weakly +ve LF, HF higher; strongly -ve FD	Diamagnetic?	LF and HF +ve, LF higher; FD lower than LF & higher than HF	Antiferromagnetic
Natural	Similarly weakly +ve LF, HF & FD	Paramagnetic	Weakly +ve LF, HF & FD	Paramagnetic	LF and HF +ve, LF lower; FD lower & strongly -ve	Diamagnetic?

ICP-MS Analysis of Soils and Plants from Experiment 3: Results

Data from the excavated soils reveal a number of differences in chemical composition from each of the features. These, along with the data from the augured soils, and the mean values for the features from each of these sources are summarised in Table 6.14.

In the excavated soil samples, while P concentrations appear to be raised in the ditches, lower levels of Al, Fe, K, Cu, Cd, Ti, Mn, Na, Zn, Ni, Cr and Pb were indicated. No obvious chemical differences were recognized in the bank material, thought perhaps to be due to the extreme plough truncation of this feature, until the data was subjected to statistical analysis. The topsoil from above the trial trench showed variations in chemical composition, with increased concentrations of Ca, Cu, P, S, Zn and Pb relative to the other contexts, whilst Al, Fe, K and Na were relatively less concentrated. The clay natural reached at the base of the ditch was relatively concentrated in Al, Fe, Mg, K, Co, Cu, Ti, Mn, Na, Ni and Cr, while P, S and Pb were relatively depleted.

Statistical analysis of the ICP-MS data for the soils indicates that there are significant differences in Ca, K, P, Pb, S and to a lesser degree (significance = 0.051) Na between features. Several of the elements have high concentrations in the topsoil and entrance, and low levels in the natural. These elements include Pb, S and P, which also have raised concentrations in the enclosure interior, and Ca, the latter also having slightly elevated bank concentrations. Conversely K and Na have low topsoil concentrations, higher levels in the natural, and raised bank concentrations. Na concentrations are also elevated in the entrance, ditch and bank samples, and depleted in the interior (Appendix 4). With the exception of Ca, those elements that have high concentrations in the bank samples (K and Na) also have high natural concentrations, tending to support the idea that the enclosure bank is derived from excavated natural material.

While the excavated soils give a more accurate indication of the elemental composition of the individual contexts, soil samples gathered by auguring are more likely to give a better impression of the elements available to plants growing above the features in a field situation as discussed earlier, and it is the combined effect of the changes in soil properties within and above the buried remains that affect the remotely sensed responses. So it is likely that these samples will provide better information over all in relation to the questions posed in this thesis. Unfortunately the data from the two sources was not directly comparable because the samples were taken from individual contexts during excavation and whole soil depths during

auguring as described and because auguring sampled more of the enclosure features than trial trenches uncovered. However, both sets contained samples associated with the ditches, and as there were augured samples from outside the enclosure, representing the undisturbed soil, it was considered acceptable to compare this to the topsoil samples taken during excavation, although this is not seen as an ideal comparison. The mean values for excavated and augured soil analyses from these features revealed that for most of the elements sampled the range of concentrations was similar for both (Figure 6.26). Exceptions to this included S, Zn, Mn and Ca, which with the exception of the high topsoil concentrations of Ca were all less concentrated in the excavated soils than in the augured samples. Statistical comparison of the means of the excavated and augured soil samples indicates that only Ca, P and Na differ significantly in the two groups (Appendix 4). Within the similar ranges, almost all of the augured ditch soils had slightly higher elemental concentrations than those measured in the excavated soils except for K, and there was some variation in the topsoil/exterior soils, but given that this was not a direct comparison this was to be expected. Overall the comparison suggests that it is acceptable to compare the characteristics of excavated and augured soil samples for this site, and given the limitations of the research undertaken for this thesis the comparisons will be made for the three Case studies on this basis.

Analysis of the plants grown in the excavated soil samples showed that in some cases, such as Pb and Zn, which were statistically significantly different (Figure 6.27; Appendix 3), watering regime did cause the concentrations to change within the same sample group, and for other elements, for example topsoil levels of Ca (Figure 6.28), available water made little difference to the concentrations although they did vary between contexts irrespective of watering regime. The obvious explanation for this is that uptake of some of the elements is affected by the amount of soil water available, and others are enhanced in the plants because there is a fundamental difference in concentrations in the soils in which they grew. The elements that are suspected of being generally enhanced in soils are those whose concentrations change little between contexts in the optimally watered plants, and include S, Cu, Pb and Zn. There was a general trend for the concentrations of elements to be higher in plants grown in natural samples, and topsoil-grown plants to have the lowest concentrations. This occurred in Al, Cr, Cu, Fe, Mn and Na. Of the remaining elements Ca and K showed no obvious patterns of variation. To be of archaeological significance in this dataset the ditch concentrations would require to be different from the natural and topsoil for a sample, as variations in the latter two could most likely be attributed to pedological processes. Consequently, for the plants analysed uptake of Fe in waterlogged samples was significant,

as were concentrations of K (ditch concentrations low in droughted plants and high in the remaining two regimes) and S (Figure 6.29).

Statistically, six elements showed significantly differing means in plant groups grown in the soils taken from individual features, irrespective of watering regime. This suggests that there were significant differences in uptake or availability of these elements between contexts. The elements shown to be significantly different include Ca, Cu, Mg, Mn, Ni and Na. Additionally Fe and Zn concentrations appeared to be significant, but less so than the main group of elements whose significance was less than 0.05 (sig. <0.05; Fe and Zn = 0.052). The results of MS measurements suggest that concentrations or perhaps oxidation states of Cu and Fe are altered in the soil samples (Table 6.12). As with the soils data there were a number of elements that had high topsoil and low natural concentrations. These include Mg, which also had elevated levels in the bank material and depressed concentrations in the inner ditch, and Ca and Zn, whose bank concentrations were also elevated. Additionally the plant analyses also indicated the reverse of this situation for certain elements, that is low topsoil and high natural concentrations, in Na, Mn, Cu and Fe, all of which also had elevated bank concentrations. Ni showed enhancement in the bank and inner ditch plants. When analysing the means of elemental concentrations on the basis of watering regime, the statistical tests indicated that only Pb and Zn differed significantly. Waterlogged plants had highest Pb and lowest Zn concentrations, while this relationship was inverted for droughted plants, with optimally watered plants displaying a mid-range concentration for both elements.

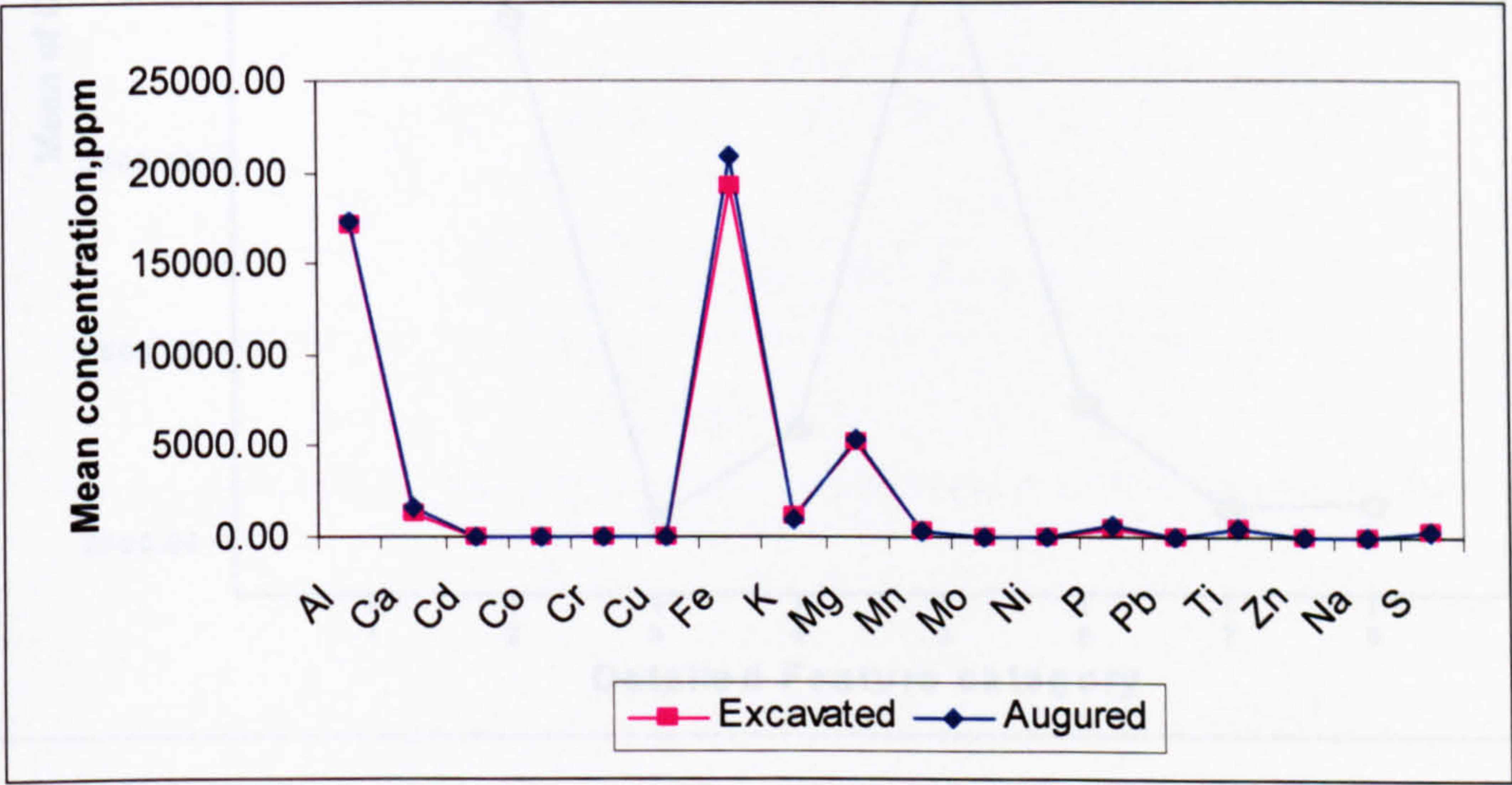


Figure 6.26:
Mean concentrations of elements in excavated and augured soils from Case study 1.

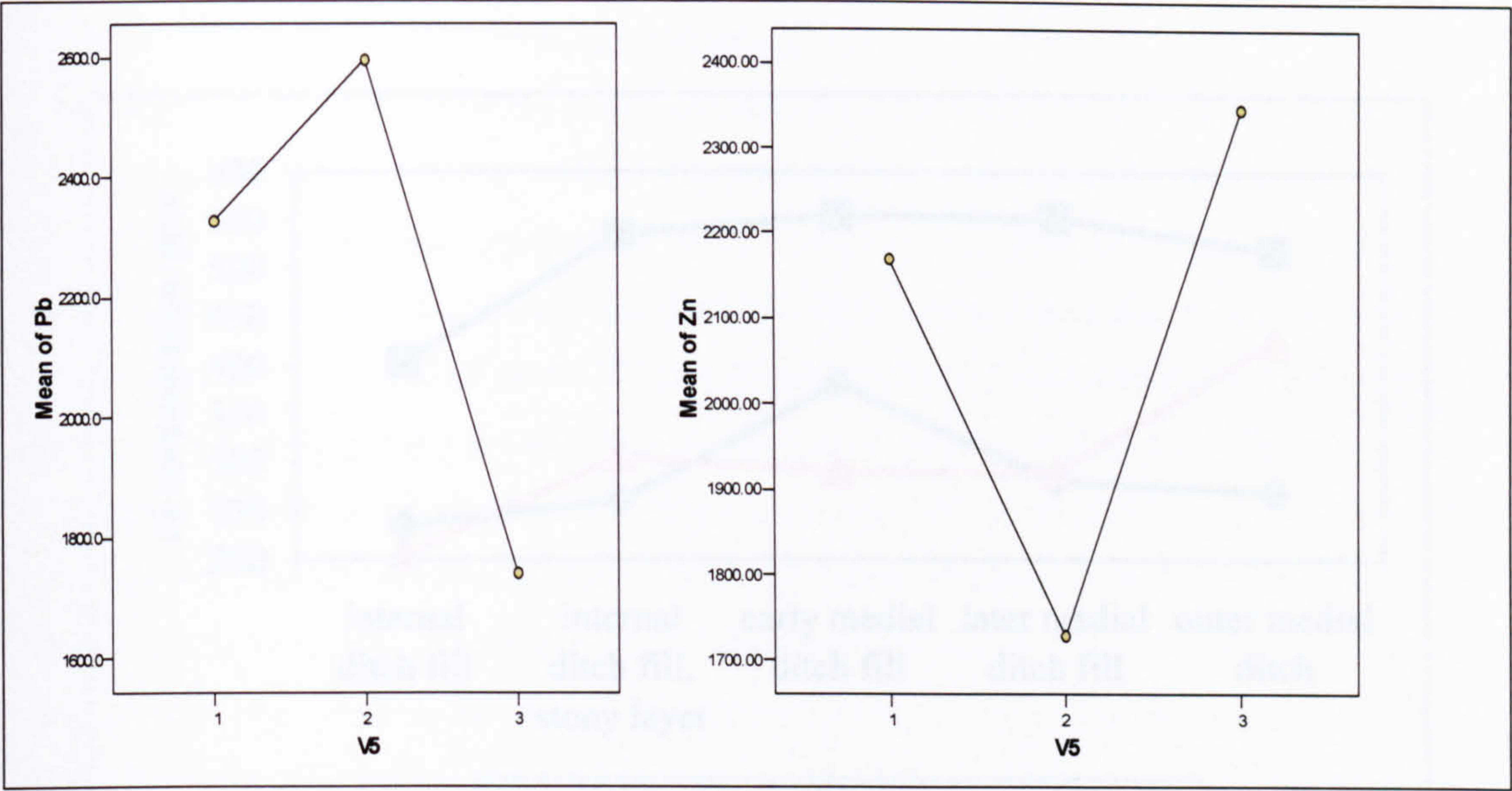


Figure 6.27:

Variations in mean Pb and Zn concentrations between plants subjected to differing watering regimes: 1: Optimally watered plants; 2: Droughted plants and 3: Waterlogged plants.

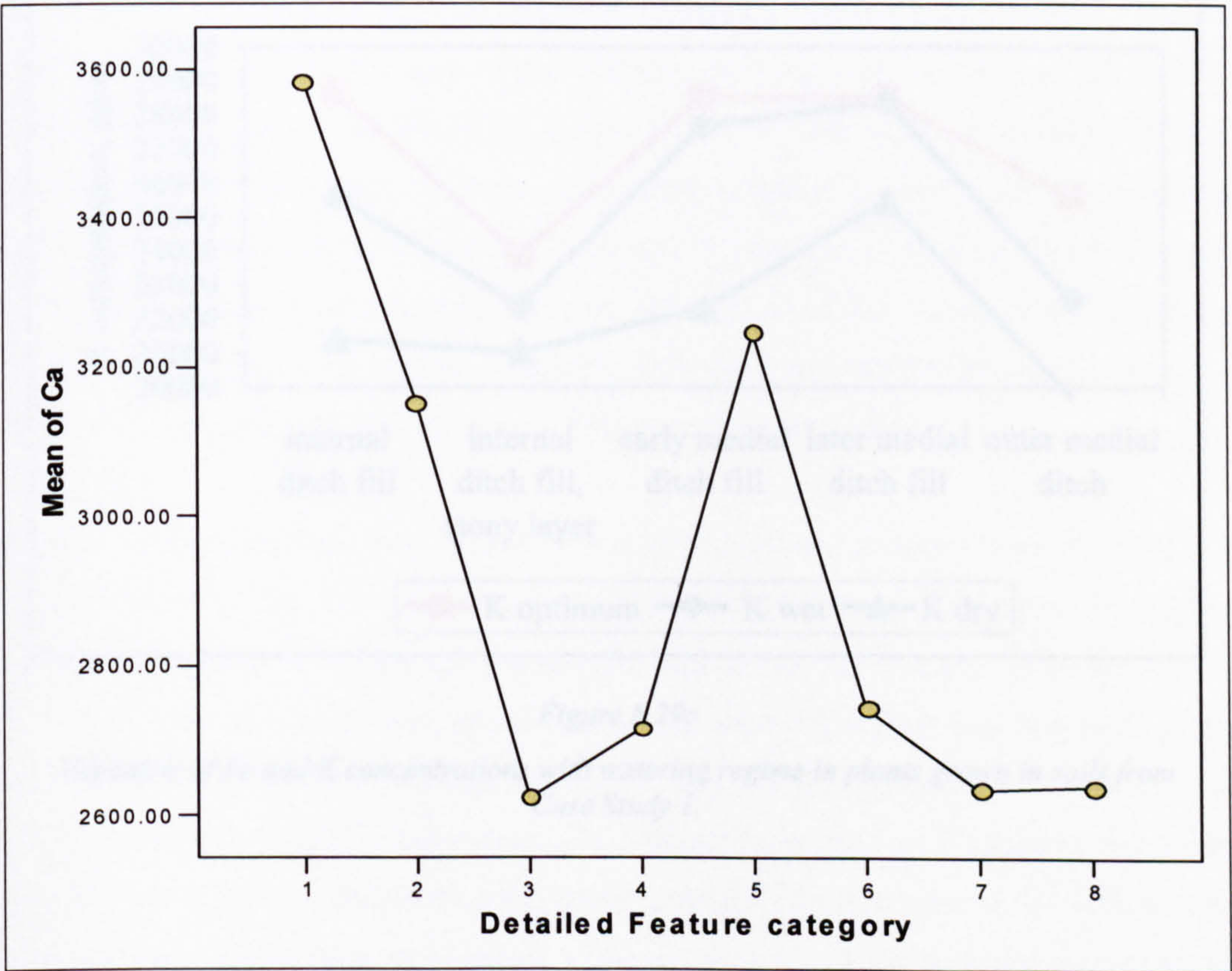


Figure 6.28:

Variations of Ca concentrations with context, but little affected by differential watering regimes. Key: 1: Topsoil; 2: Bank/Subsoil; 3: Outer medial ditch; 4: medial ditch fill; 5: Later ditch fill; 6: Internal ditch fill; 7: Internal ditch fill, stony layer; 8: Natural.

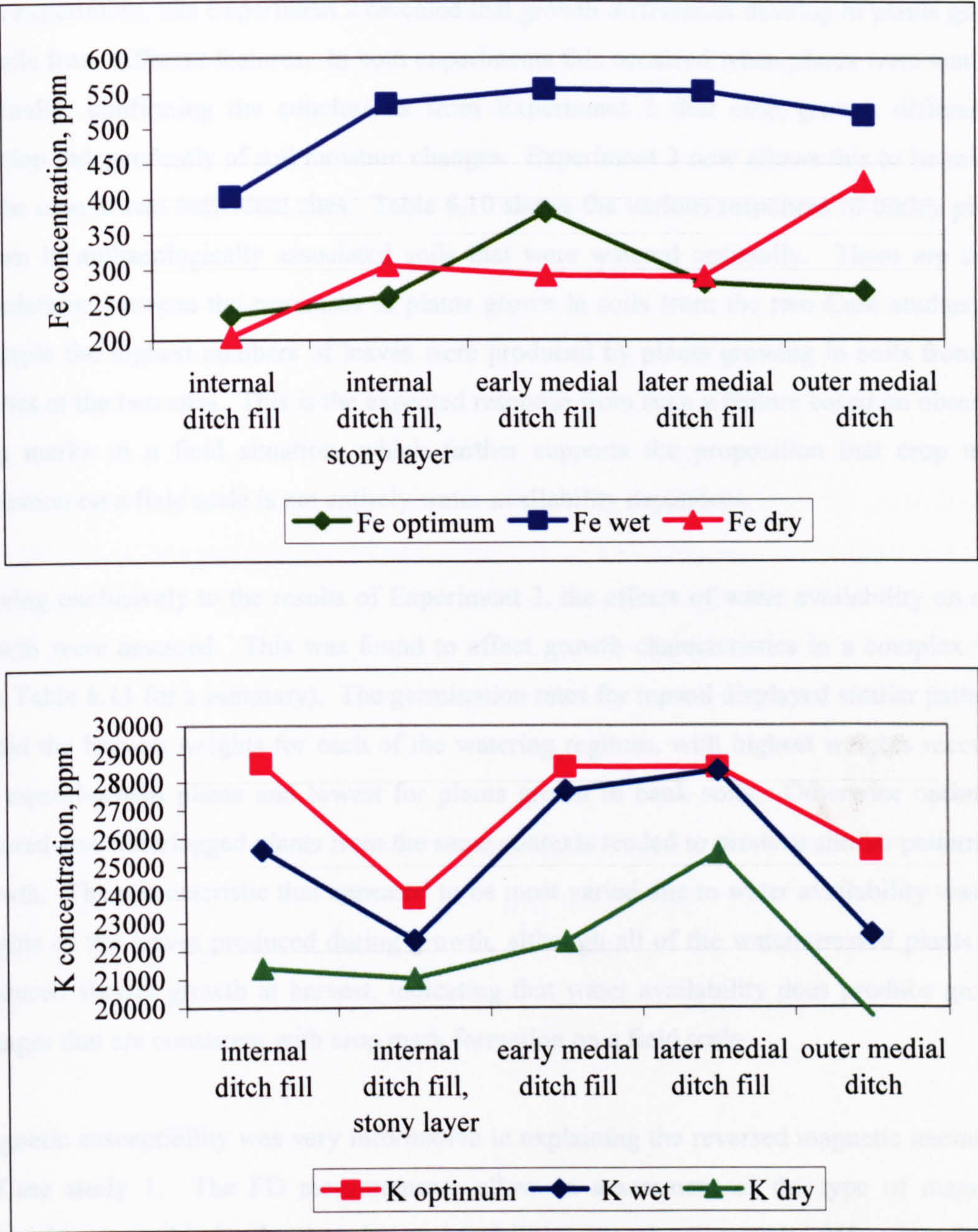


Figure 6.29:
Variation of Fe and K concentrations with watering regime in plants grown in soils from Case Study 1.

Summary of Experiment 3 Growth Experiments

This experiment, like Experiment 2 revealed that growth differences develop in plants grown in soils from different features. In both experiments this occurred when plants were watered optimally, confirming the conclusions from Experiment 2 that crop growth differences develop independently of soil moisture changes. Experiment 3 now allows this to be said to be the case at two individual sites. Table 6.10 shows the various responses of barley plants grown in archaeologically associated soils that were watered optimally. There are some correlations between the responses of plants grown in soils from the two Case studies, for example the highest numbers of leaves were produced by plants growing in soils from the ditches at the two sites. This is the expected response from such a feature based on observed crop marks in a field situation, which further supports the proposition that crop mark formation on a field scale is not entirely water-availability dependent.

Moving exclusively to the results of Experiment 3, the effects of water availability on crop growth were assessed. This was found to affect growth characteristics in a complex way (see Table 6.11 for a summary). The germination rates for topsoil displayed similar patterns, as did the harvest weights for each of the watering regimes, with highest weights recorded for topsoil-grown plants and lowest for plants grown in bank soils. Otherwise optimally watered and waterlogged plants from the same contexts tended to produce similar patterns of growth. The characteristic that appeared to be most varied due to water availability was the heights of the leaves produced during growth, although all of the water-stressed plants had produced shorter growth at harvest, indicating that water availability does produce growth changes that are consistent with crop mark formation on a field scale.

Magnetic susceptibility was very informative in explaining the reversed magnetic anomalies at Case study 1. The FD measurements allow an assessment of the type of magnetic materials responsible for the changing susceptibilities in each soil sample. MS values for the plant samples varied significantly depending on the watering regime that had been applied during growth. This is a significant result not only for the understanding of crop mark formation, but also for the link between it and magnetic survey, as it suggests that certain elements have limited availability under certain watering regimes, such as Fe, which means that they are present in different oxidation states in the soils. In Table 6.14 the elements that the MS information suggests are likely to be significant in bringing about the changes and those that ICP-MS analysis indicate are significantly enhanced or depleted relative to the concentrations of the remaining samples are summarised. The table indicates that a number

of elements feature as significant not only for the soils analysed but also for the plants and relative to magnetic susceptibility information. These elements include Fe, which is enhanced in the plants and depleted in the soils associated with the ditches, and also indicated as being associated with the magnetic effect detected in the MS measurements of the ditch-grown plants. S can be seen to be enhanced over the enclosure entrance and ditches, and depleted in the bank and natural samples for soils and depleted in ditch-grown plant samples.

The question remains then of how much remotely sensed responses are a result of the factors that cause differential growth when there are no soil moisture differences, and how much is due to differential water retention. This can be addressed partly by continuing to look at soil chemical differences and uptake by plants to see whether there are patterns identifiable where the differential growth exists, and also by examining the effects of soil moisture changes without the variables introduced by growth in 'archaeological' soils. This is done in Experiments 4 and 5. Only when all of the data is gathered together in the concluding part of this chapter can these trends be examined to determine whether they are indicative of the wider situation, or whether the results are applicable only to this particular site, or group of sites.

Case Study 3 has aerial and excavated information, poor geophysical results and no barley experimental work. The use of this site represents a first step towards applying the results of all of this experimental work to a field situation and towards addressing the problem of how to gather information from a site that is largely unresponsive to remote sensing methods. This is addressed in section 6.7.

Table 6.14: Soil Chemical Differences Between Case Study 1 Features

a) soils

Features	Augured Soils	Excavated Soils	Averaged Soils	Significant?	Statistically Significant
Entrance high	Al, P, Pb, S	No sample	Ca, P, Pb, S	P, Pb, S	Ca, P, Pb, S
Entrance low	Mn, Ti	No sample	Mg, Mn	Mn	None
Inner ditch high	Al Cd Co Cr Fe K Mg Mn Ti	None	None	None	K
Inner ditch low	P, S	None	None	None	P, S
Ditches high	P, Pb, S	P	Ti	P, S	P, Pb, S
Ditches low	Cu, Pb, Fe, Mn	Al Fe K Cu Cd P Ti Mn Cr Pb	None	Cu, Pb, Fe, Mn	P, Pb
Bank high	Ca, P, Pb, S, Co, Cu, K	None	Cd, Co, Fe, ~K, Mn, Ti	Co, K	Ca, K, P, Pb, S
Bank low	Co, Cu, Fe K, Mg, Mn, Ca, Cr, Pb, S	None	S	S	Ca, K, Pb, S
Bank reverse anomaly	Ca, Co, Cr, Cu, Fe, K, Mg, Mn, Ti, Na	No sample	None	None	Ca, K, Na
Interior high	P, S	None	Cr, Cu, Ni, ~P, Pb	P	P, S, Pb
Interior low	Na	None	Na	Na	Na
Exterior high	Al	No sample	Al, ~P	Al	P
Exterior low	Fe, K, Ti	No sample	Cd, Fe	Fe	K
Topsoil high	No sample	Ca, Cu, P, S, Pb	Ca, P, Pb	Ca, P, Pb	Ca, P, Pb, S
Topsoil low	No sample	Al, Fe, K, Na	Co, K, Mg, Na	K, Na	K, Na
Natural high	No sample	Al Fe Mg K Co Cu Ti Mn Cr	K, Mg, Ti	K, Mg, Ti	K,
Natural low	No sample	P, S, Pb	Ca, Cr, P, S	P, S	Ca, P, Pb, S
No pattern	Cd, Mg, Ni, Al, Cd, Zn	Co, Zn, Ni, Cr		Ni, Zn	None

b) plants

<i>Features</i>	<i>Plants</i>	<i>Plant MS</i>	<i>Soil MS</i>	<i>Statistically Significant</i>
Entrance high	None	None	?Diamagnetic	Ca, Cu, Mg, Mn, Ni, Na ~Fe, ~Zn
Entrance low	None	None	None	
Inner ditch high	None	None	None	
Inner ditch low	None	None'	None	
Ditches high	Fe (wet), K (dry)	?Paramagnetic	?Diamagnetic	
Ditches low	K (wet & optimum), S	None	None	
Bank high	None	?Ferrimagnetic	?Paramagnetic/ ferrimagnetic	
Bank low	None	None	None	
Bank reverse anomaly	None	None	None	
Interior high	None	None	?Diamagnetic	
Interior low	None	None	None	
Exterior high	None	None	None	
Exterior low	None	None	None	
Topsoil high	None	None	?Diamagnetic	
Topsoil low	None	None	None	
Natural high	None	None	?Paramagnetic	
Natural low	None	None	None	
No pattern	None	None	None	

6.5 Experiment 4: Water availability and Its Effects on the Growth and Development of Spring Barley

In this experiment the only cultural factor to be varied was water availability. This was the first of the remaining two experiments to use proprietary composts as a growing medium, as detailed in Chapter 3. As these composts are formulated to support optimum growth, any differences recorded should be due entirely to the effects of water availability. Table 6.15 summarises the treatments assigned to each pot and the progress of plant growth to each of the harvests. Harvests were carried out at three intervals to allow an assessment of growth at tillering and flowering stages, and finally at maturity. At each of the three harvests the wet and dry weights for aerial growth were recorded, together with the maximum height of each plant, and the number of tillers, leaves, and, at later stages, of flower heads. The experiment was set up on 10 May 2000 and the first harvest took place on 5 June.

Harvest 1

A visual assessment at this stage revealed that two of the pots containing plants that had been waterlogged (36 and 19) had straight, rigid, pale green growth. In contrast two of the pots that had been watered optimally (22 and 53) had a dark green bushy habit with soft floppy foliage. Plate 6.6 shows that even during early growth stages, visual differences between plants undergoing the three watering regimes had developed. This is likely to have an impact on a field-scale that would be noticeable during early aerial reconnaissance. The maximum heights of the individual plants were similar for optimally watered and waterlogged plants, but droughted plants appeared shorter even at this early stage

For this experiment, unlike the data for Experiments 2 and 3, data for the individual pots is presented here rather than the mean values because the smaller datasets from each harvest are easier to visualise, and the variations in growth characteristics are smaller for these plants. This smaller variability is assumed to be due to the use of compost as opposed to archaeological soils, which have greater natural variability in their properties.

The table shows, and data is depicted in Figures 6.30 to 6.32, that heights were tallest for optimally watered plants, and quite similar for those that had been waterlogged, with droughted plants being shorter on average than the other groups (Figure 6.30). Wet weights revealed a similar trend, although waterlogged plant weights were more depressed than those

that were optimally watered. This trend towards enhanced growth in optimally watered plants, and reduced growth in water-stressed plants, with lowest values recorded for those that had been droughted, was also recorded for the production of tillers (Figure 6.31), and numbers of leaves. This confirms that from germination and throughout the early stages of development, barley growth is adversely affected by any form of water stress, with droughting having the most deleterious effect. Figure 6.32 shows the mean values for these characteristics, which confirm the trends identified in the data for the individual pots.

Table 6.15: Development of Plants Harvested at Tillering Stage, Experiment 4

<i>Pot No</i>	<i>Treatment</i>	<i>Average Height, cm</i>	<i>No of Leaves</i>	<i>No of Tillers</i>	<i>Wet Weights, g</i>	<i>Dry Weights, g</i>
4	Waterlogged	29.6	144	44	40.3	4.4
11	Droughted	28.7	172	51	30.6	4.2
14	Waterlogged	35.2	198	53	53.2	7.2
17	Droughted	3.2	161	46	26.2	4.7
19	Waterlogged	47.2	222	61	79.7	9.6
20	Optimum	50.8	264	70	129.8	12.3
22	Optimum	51.4	267	66	119.1	11.9
23	Waterlogged	46.9	214	58	68.7	8.2
28	Optimum	44.0	206	55	77.2	8.5
34	Droughted	37.6	179	49	39.7	6
35	Waterlogged	46.7	180	49	52.2	7.5
36	Waterlogged	45.8	173	47	49.2	7
37	Optimum	48.5	230	60	85.8	9.6
44	Optimum	44.7	220	59	95.9	9
50	Droughted	45.4	206	54	85.3	8
51	Waterlogged	44.2	164	45	40.6.	5.5
53	Optimum	50.1	263	71	109.3	10.6
54	Droughted	44.9	185	49	62.9	7.1

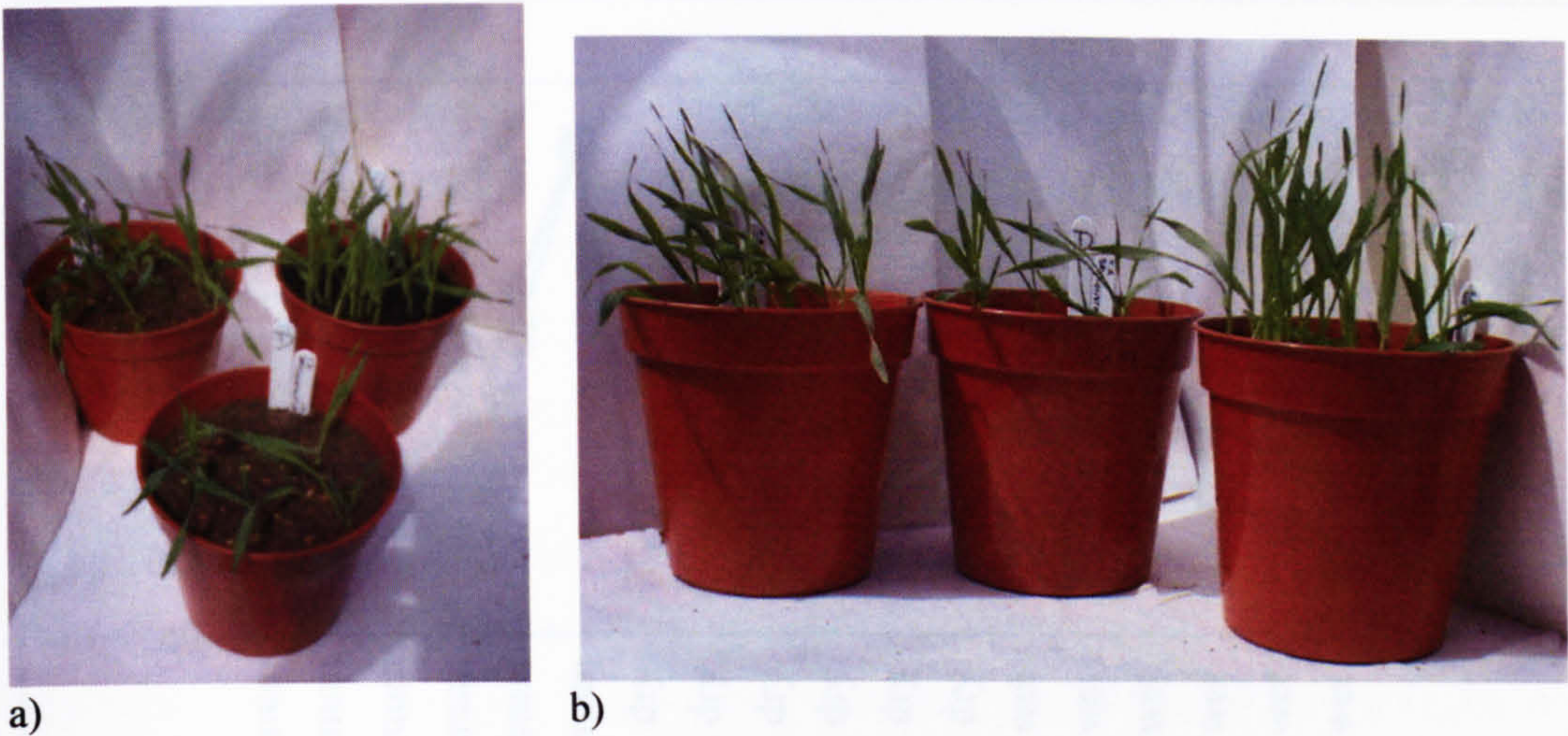


Plate 6.6:

Experiment 4: 19/5/00. a) from left to right at the back, Optimally watered; Waterlogged, and in the foreground, Droughted plants and b) from left to right, Optimum; Droughted and Waterlogged plants.

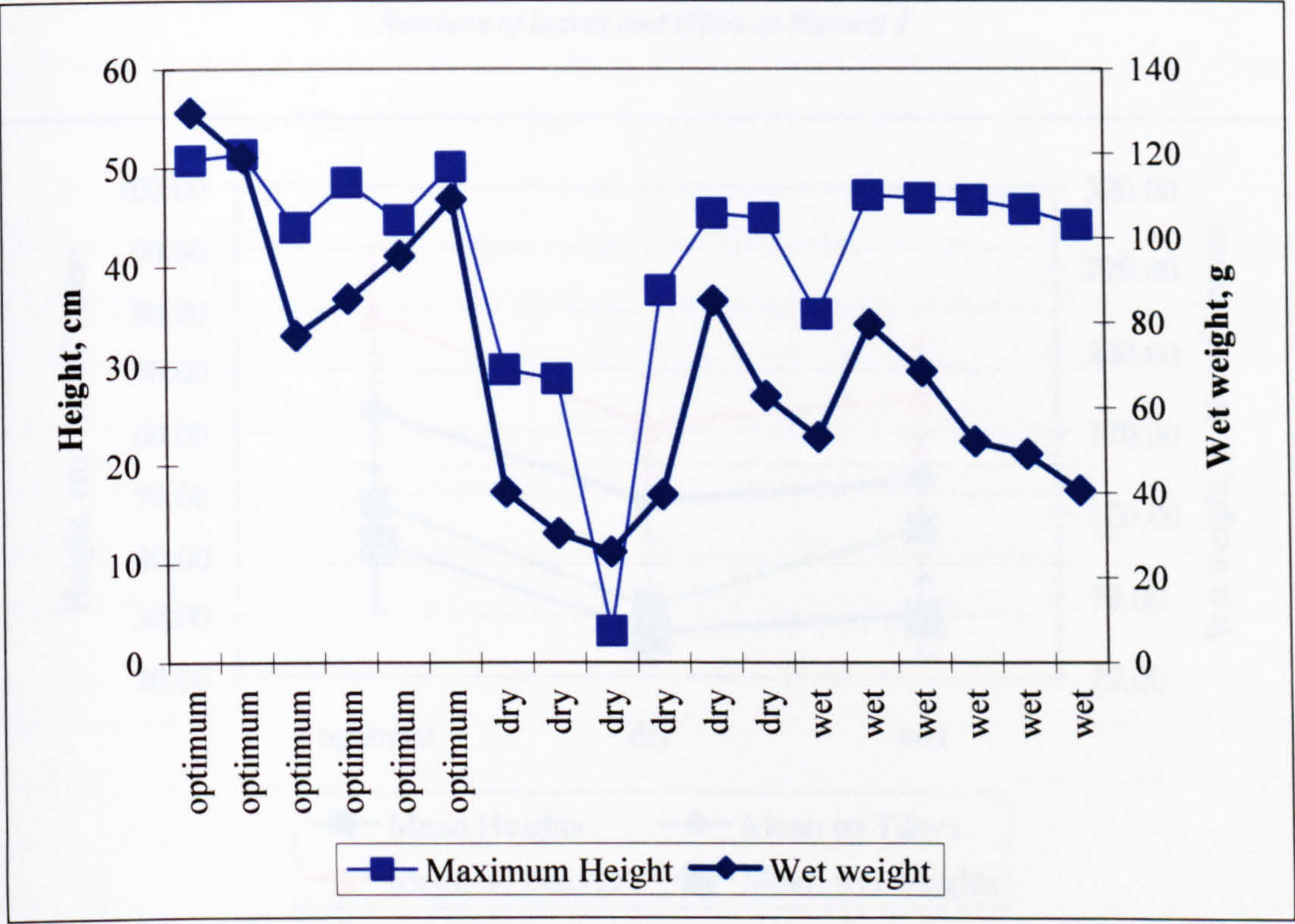


Figure 6.30:

Harvest 1 plants showing maximum height and wet weights of the plants at harvest.

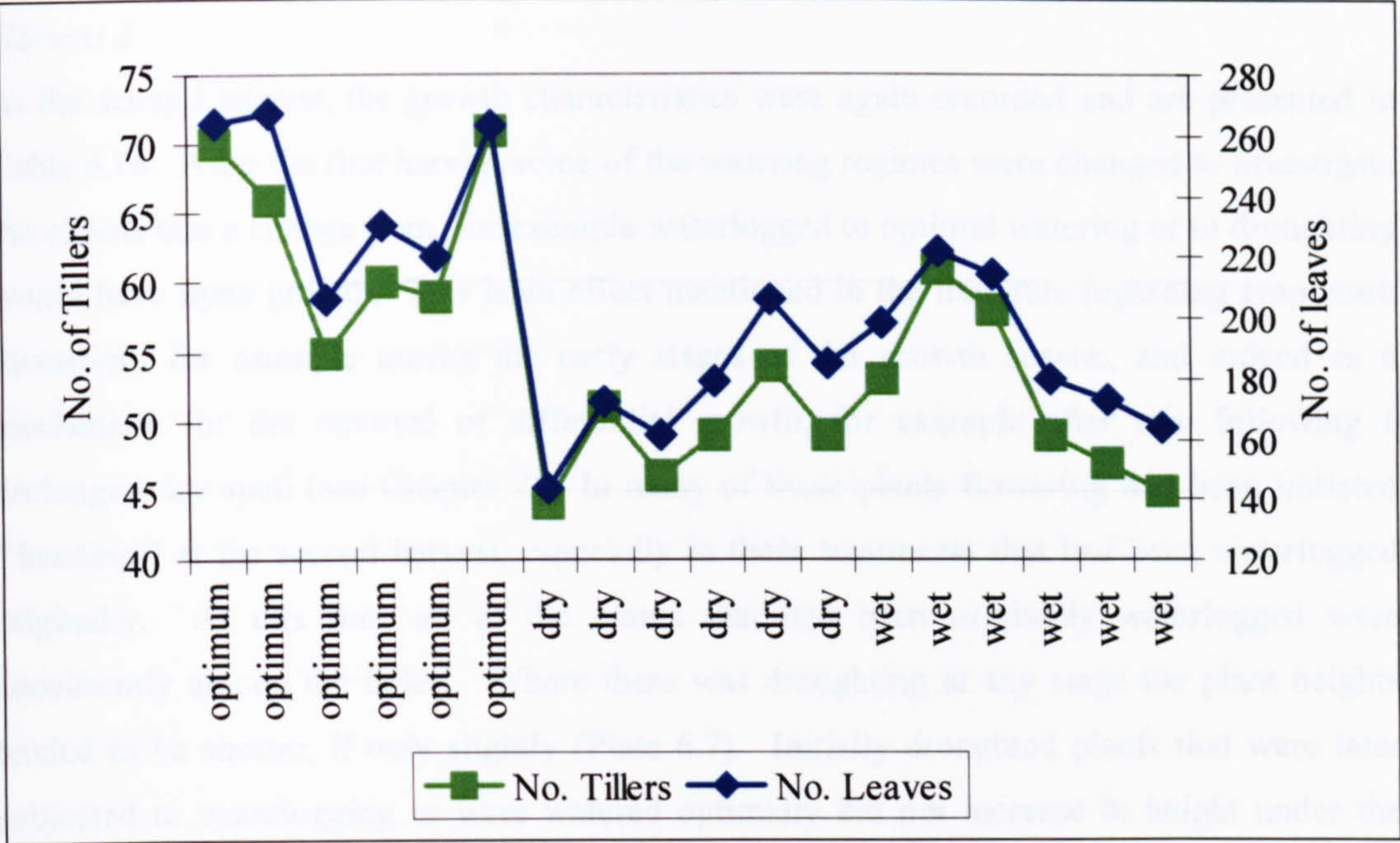


Figure 6.31:
Numbers of leaves and tillers at Harvest 1

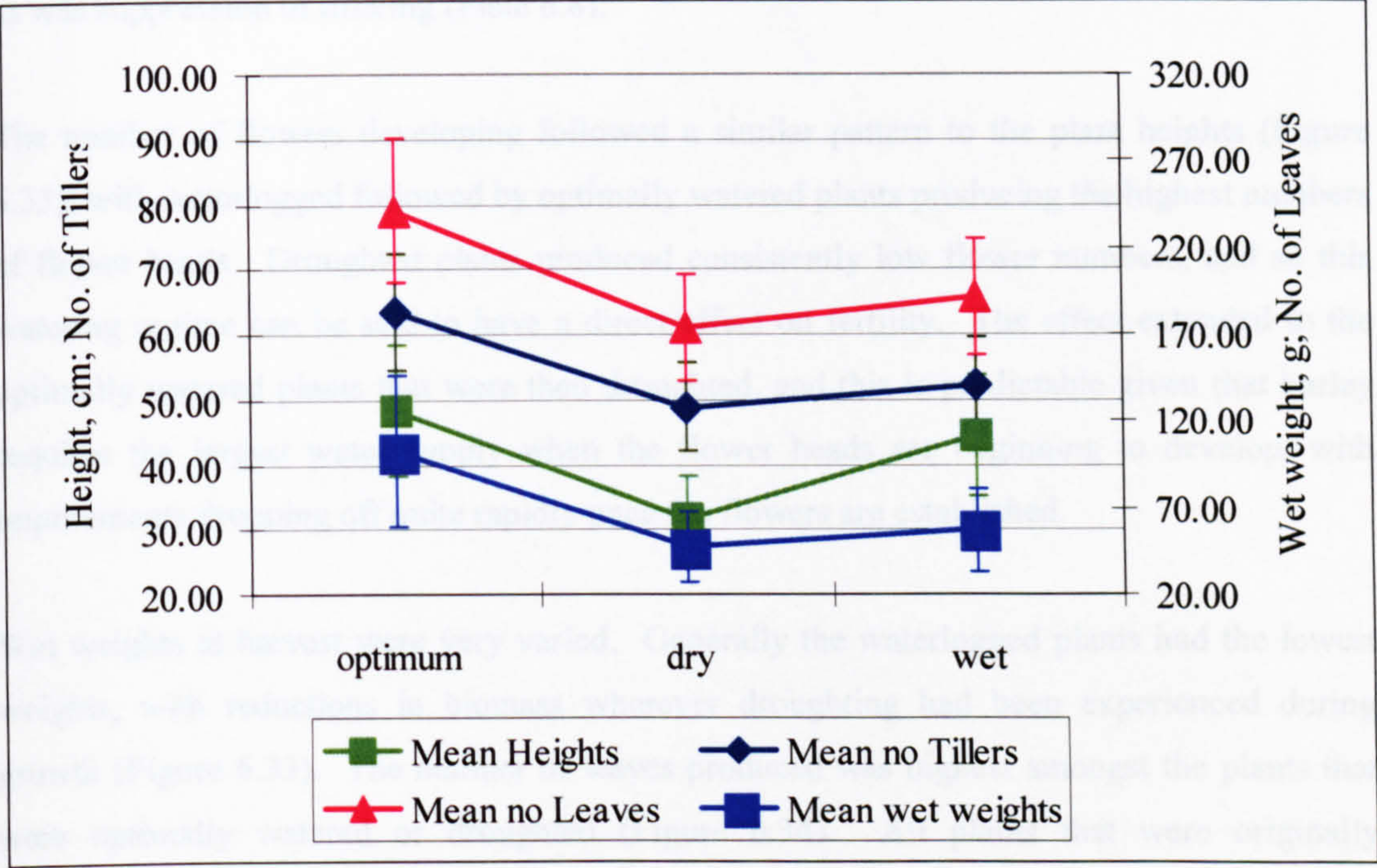


Figure 6.32:
Mean maximum heights wet weights, numbers of leaves and tillers for Harvest 1 plants.

Harvest 2

At the second harvest, the growth characteristics were again recorded and are presented in Table 6.16. After the first harvest some of the watering regimes were changed to investigate the effects that a change from, for example waterlogged to optimal watering or to droughting would have upon growth. This is an effect mentioned in the literature regarding crop mark formation, for example during the early stages of the growth season, and indeed as a mechanism for the removal of differential growth, for example after rain following a prolonged dry spell (see Chapter 2). In many of these plants flowering had been initiated ('heading') at the second harvest, especially in those treatments that had been waterlogged originally. At this time all of the plants that had been originally waterlogged were consistently among the tallest. Where there was droughting at any stage the plant heights tended to be shorter, if only slightly (Plate 6.7). Initially droughted plants that were later subjected to waterlogging or were watered optimally did not increase in height under the new watering regimes sufficiently to catch up with plants developing under these regimes initially, although those that were later waterlogged were the closest to bridging this gap. Differences in foliage colour were also clearly visible in the waterlogged groups particularly, as was suppression of tillering (Plate 6.8).

The number of flowers developing followed a similar pattern to the plant heights (Figure 6.33), with waterlogged followed by optimally watered plants producing the highest numbers of flower heads. Droughted plants produced consistently low flower numbers, and so this watering regime can be said to have a direct effect on fertility. The effect extended to the optimally watered plants that were then droughted, and this is predictable given that barley requires the largest water supply when the flower heads are beginning to develop, with requirements dropping off quite rapidly once the flowers are established.

Wet weights at harvest were very varied. Generally the waterlogged plants had the lowest weights, with reductions in biomass wherever droughting had been experienced during growth (Figure 6.33). The number of leaves produced was highest amongst the plants that were optimally watered or droughted (Figure 6.34). All plants that were originally waterlogged produced significantly smaller numbers of leaves than plants subject to any other watering regime. Even those waterlogged plants that were later droughted or watered optimally still produced significantly fewer leaves. Conversely, the number of dead leaves present was highest in waterlogged plants and lowest in droughted ones. In the optimally watered plants the numbers of dead leaves present at harvest increased in those plants that

were changed to a droughting regime, but this effect was not observed in those plants that were changed to a waterlogged environment. The increase in leaf mortality in optimally watered plants that were later droughted is due to high leaf production in optimally watered plants resulting in there being more to leaves to support with less water when the regime was changed to droughting (See Experiment 3 and Marschner 1995). Plants that had undergone droughting had the highest numbers of tillers (Figure 6.30), and the waterlogged plants produced the lowest numbers (see Plate 6.7 and 6.8). When droughted plants were watered optimally or waterlogged the numbers of tillers produced decreased, confirming that this is a response to droughting stress. Within the individual watering regimes, all plants that were constantly subjected to either droughting, waterlogging or optimal watering produced the largest numbers of tillers relative to those in each group whose initial regime was changed after Harvest 1.

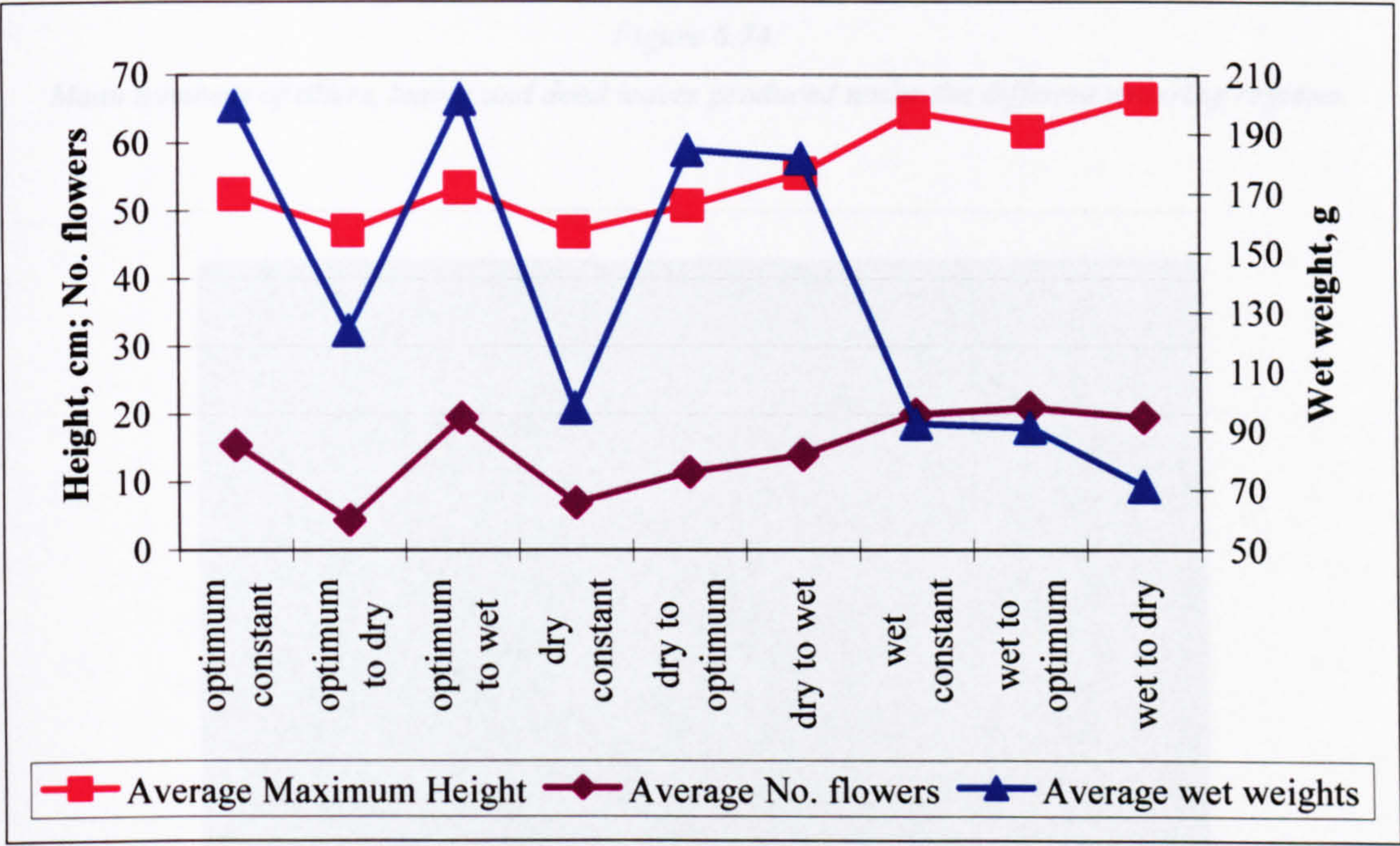


Figure 6.33:
Mean maximum heights, number of flowers and wet weights at Harvest 2 for plants grown under differing watering regimes

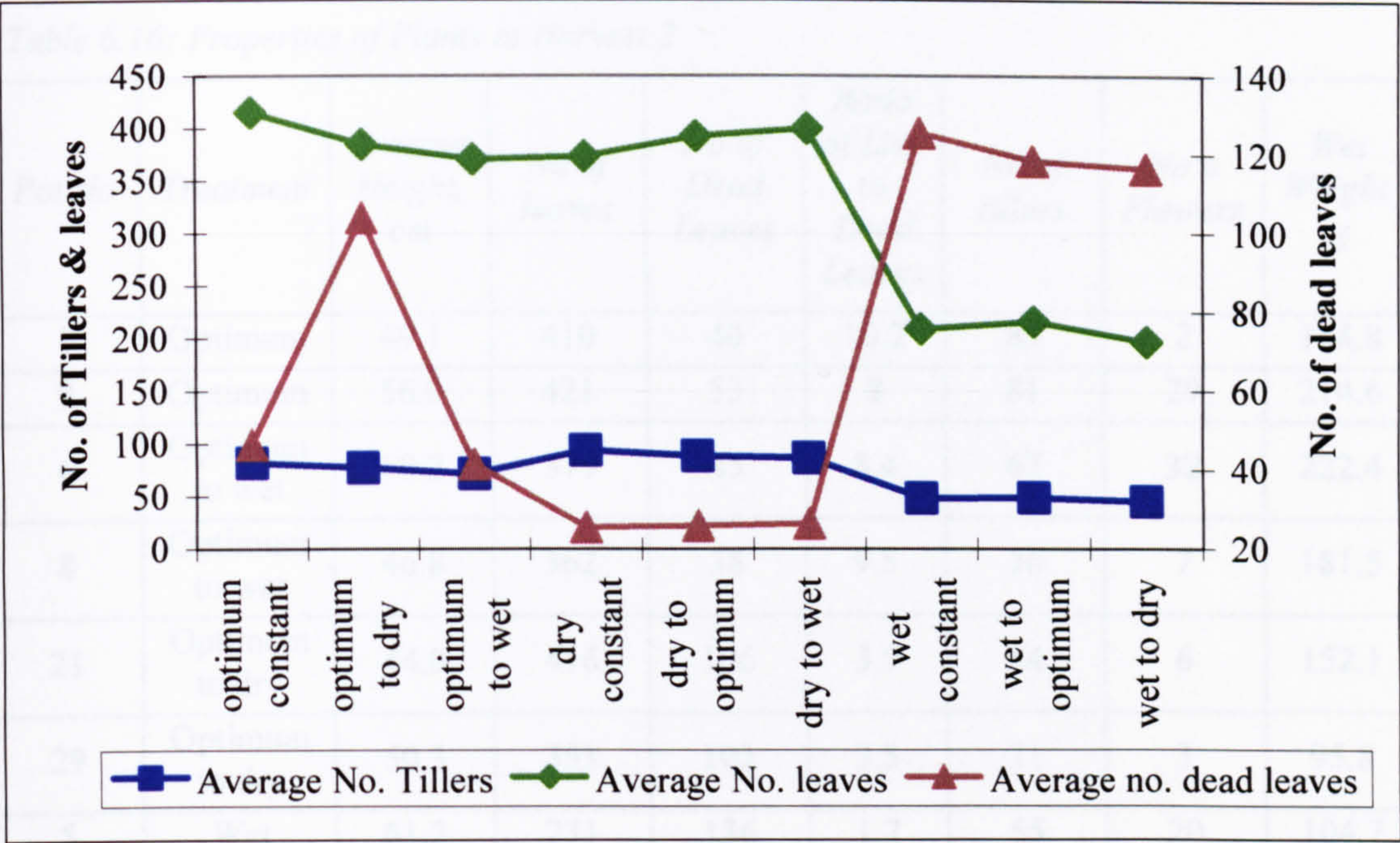


Figure 6.34:
Mean numbers of tillers, leaves and dead leaves produced under the different watering regimes.

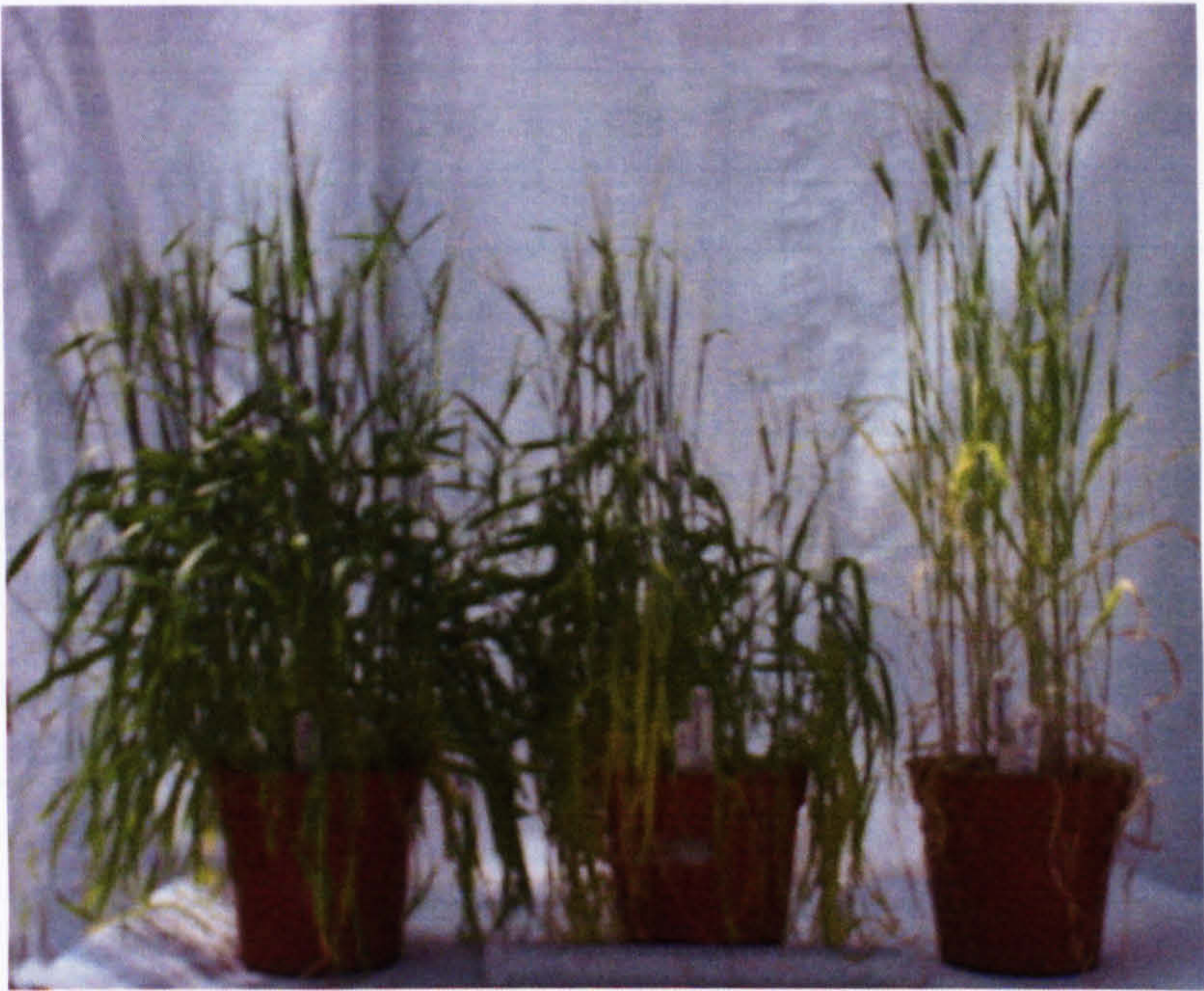


Plate 6.7:
Shortened growth in droughted plants (centre) relative to optimally watered (left) and waterlogged (right) plants before Harvest 2.

Table 6.16: Properties of Plants at Harvest 2

Pot No	Treatment	Average Height, cm	No of leaves	No of Dead Leaves	Ratio of Live to Dead Leaves	No of tillers	No o Flowers	Wet Weight, g
1	Optimum	49.1	410	40	10.2	83	2	184.8
9	Optimum	56.0	421	53	8	81	29	214.6
6	Optimum to wet	60.2	379	45	8.4	67	32	222.4
8	Optimum to wet	46.8	362	38	9.5	76	7	181.5
21	Optimum to dry	44.0	416	106	3.9	84	6	152.1
29	Optimum to dry	50.3	353	102	3.5	71	3	95.8
5	Wet	61.2	231	136	1.7	55	20	104.7
26	Wet	67.9	187	115	1.6	42	20	80.4
2	Wet to Optimum	59.6	220	121	1.8	50	20	99.2
31	Wet to Optimum	63.9	212	116	1.8	48	22	83.
25	Wet to dry	65.7	204	105	2	47	19	74.7
49	Wet to dry	67.5	190	128	1.5	44	20	68.1
39	Dry	47.2	387	30	12.9	96	6	97.9
52	Dry	46.7	359	21	17.1	92	8	97.8
3	Dry to optimum	49.7	344	10	34.4	78	4	168.2
48	Dry to optimum	51.9	441	42	10.5	99	19	201.4
15	Dry to wet	49.8	351	26	13.5	79	5	149.4
24	Dry to wet	61.3	448	27	16.6	94	23	214.7



Plate 6.8:
Lack of tillering in mature waterlogged Experiment 4 plants.

Harvest 3

Finally, the remaining plants were harvested and the growth characteristics were again recorded for each pot of plants (Table 6.17). At this final harvest the characteristics were counted per pot as opposed to per plant as had been done previously. This was necessary because the plants had put on so much top growth that it was impossible to separate out the leaves of each individual plant. This does not pose a problem in terms of consistency of presentation of the results however, given the decision to present all of the data as per pot figures.

At the final harvest the tallest plants were those that had been watered optimally or waterlogged at some point (Figure 6.35), and wherever droughting had occurred during growth the plants were stunted. Final wet weights of the mature plants (Figure 6.35) tended to be elevated where the plants were optimally watered, or where treatment was changed to waterlogging, for example optimally watered plants that were then waterlogged, and droughted plants that became waterlogged or optimally watered, although there were wide overall variations in the weights recorded. Wherever the plants were initially waterlogged, however, the final weight of aerial growth was depressed. The numbers of tillers (Figure 6.36) continued to be higher where plants suffered droughting and lower for waterlogged plants, and the highest numbers of tillers were counted in those plants that were originally

watered optimally and then droughted. Tiller development was suppressed in plants that were originally waterlogged, and also in those plants whose watering regime had been changed to waterlogged during growth. It can be assumed that leaf production followed the same trend as tillering (as is the case for Harvest 2 plants) but the numbers of leaves were so high, and untangling them impossible without breaking them so this characteristic was not counted for the Harvest 3 plants. It is clear from Plate 6.9 however that waterlogged plants produced the lowest numbers of leaves and optimally watered plants the highest, whilst droughted ones represent the average, and were shorter and darker in appearance than the optimally watered plants.

Flowering was also suppressed in originally waterlogged plants, and this effect could be seen in constantly droughted plants too. This is likely to be due to production of fewer tillers, each of which produce flowers, in waterlogged plants, and to insufficient water supply for development of flower heads in the droughted plants. Generally however, the relationship between water availability and flower production is neither a clear one, nor one that is particularly relevant to this thesis since any crop marks developing would have appeared long before this mature stage of the crop's life cycle.

A limited number of the plants could be analysed using ICP-MS (see below) and the results of this examination are presented and discussed in that section.

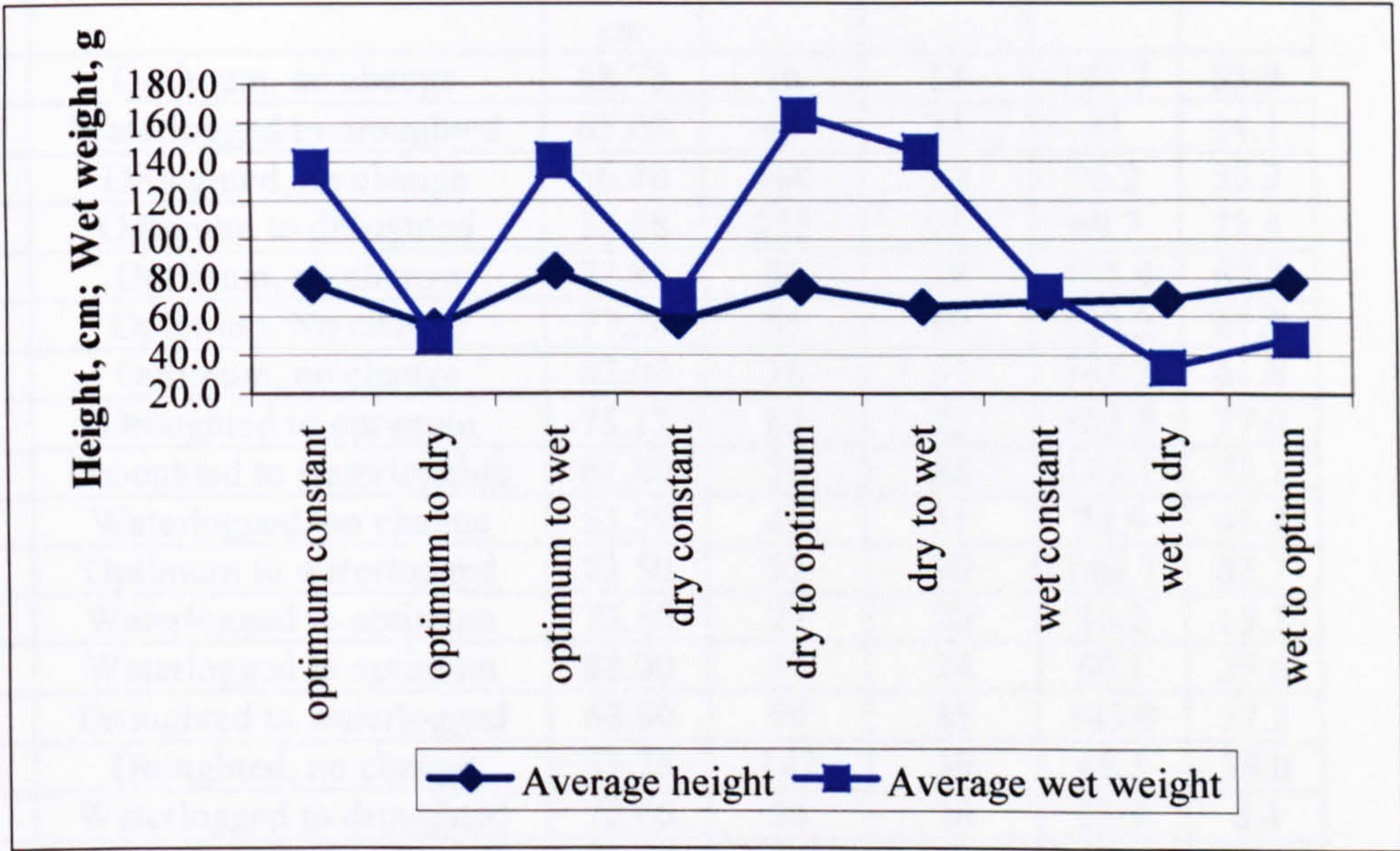


Figure 6.35:
Mean maximum heights and wet weights at Harvest 3 for differentially watered mature plants.

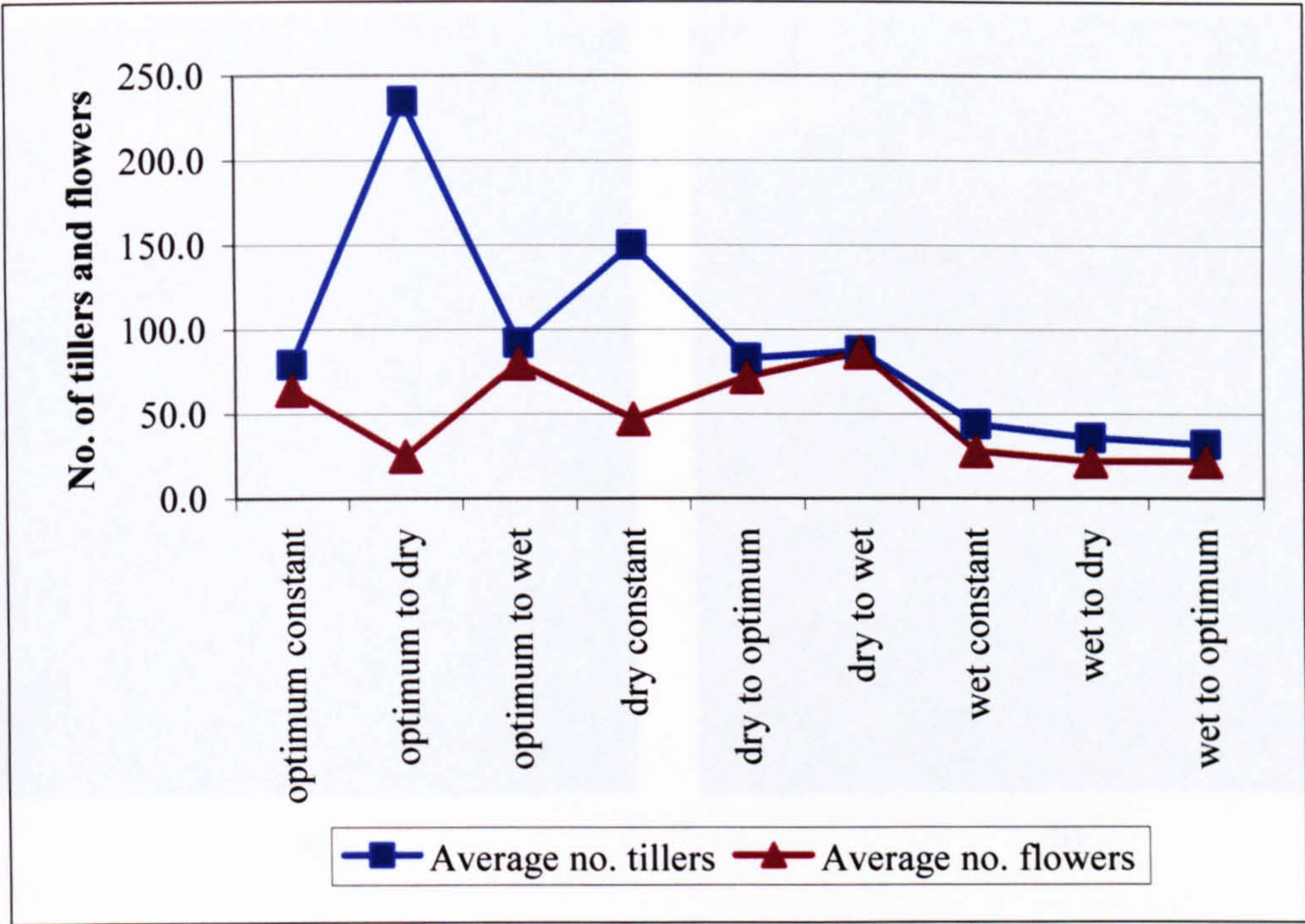
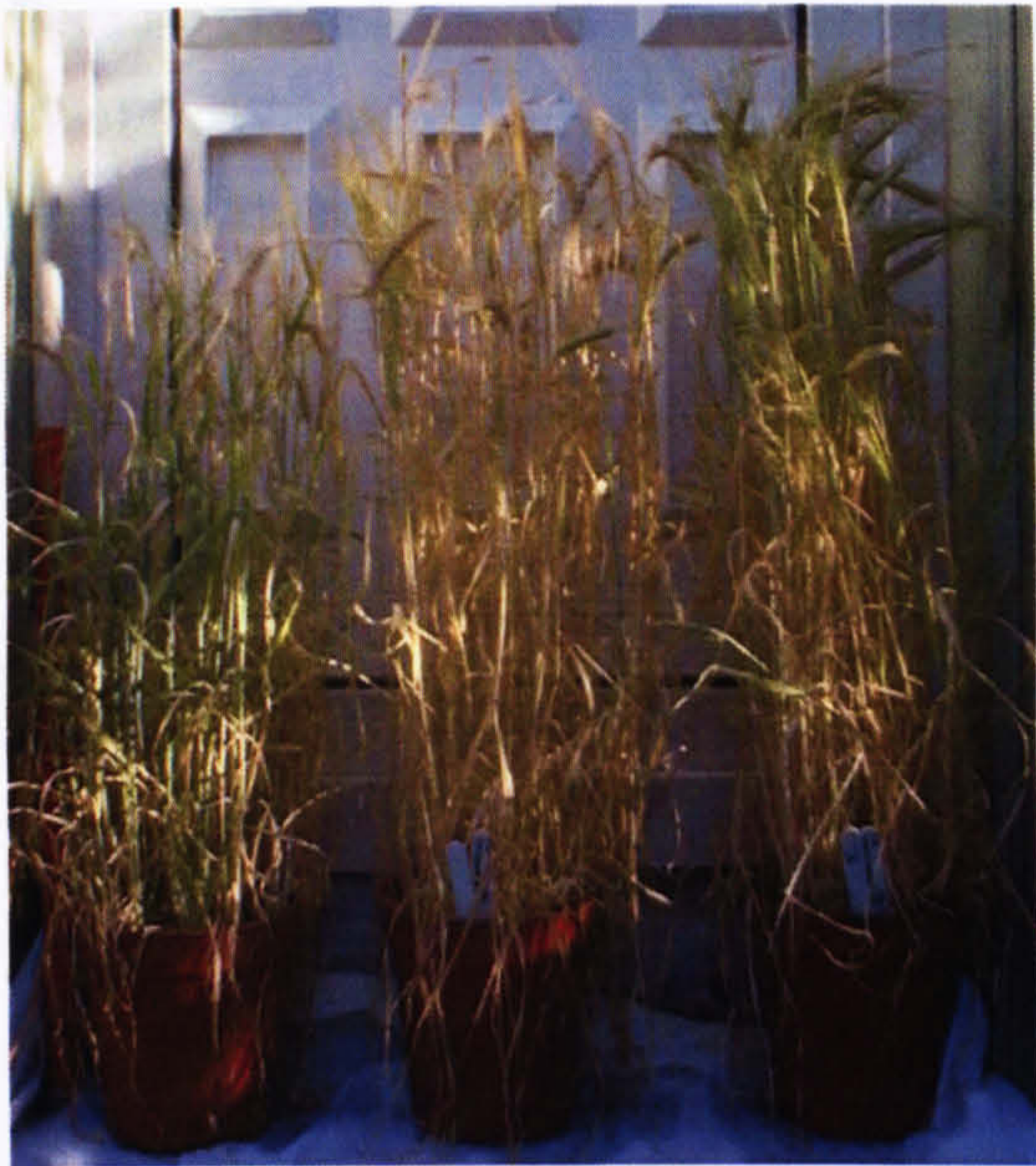


Figure 6.36:

Mean numbers of tillers and flowers produced by differentially watered plants at maturity.

Table 6.17: Development of Plants Harvested at Maturity

Pot No	Treatment	Max Height (av) cm	No of Tillers	No of flowers	Wet Wt g	Dry wt g
7	Optimum, no change	68.75	76	53	107.7	53.9
10	Waterlogged to droughted	65.00	48	24	41	14.1
12	Droughted, no change	56.40	168	54	75.2	33.2
13	Optimum to droughted	54.68	235	25	49.7	23.4
16	Optimum, no change	77.85	80	68	152.8	63.7
18	Optimum. No change	77.20	85	69	127.2	67.9
27	Optimum, no change	82.00	76	67	162.3	61.8
30	Droughted to optimum	75.12	83	72	163.8	77.0
32	Droughted to waterlogging	61.40	76	88	145.7	73.1
33	Waterlogged, no change	53.59	49	31	79.9	45.4
38	Optimum to waterlogged	83.50	92	80	140.7	83.7
40	Waterlogged to optimum	73.50	27	20	36.2	13.2
41	Waterlogged to optimum	82.00	37	24	60.1	23.6
42	Droughted to waterlogged	68.60	99	85	143.9	57.2
43	Droughted, no change	53.25	147	39	65.1	36.0
45	Waterlogged to droughted	72.66	24	20	25.9	8.4
46	Waterlogged, no change	81.16	39	25	66.3	28.4
47	Droughted. No change.	63.37	136	48	71.1	34.5



a)



b)



c)

Plate 6.9:

Growth differences at harvest: a) droughted, optimally watered and waterlogged constantly; b) optimally watered plants changed to droughted, constant optimally watered and waterlogged and c) waterlogged plants changed to droughted, optimum and constantly waterlogged.

ICP-MS Analysis of Plants Grown Under the Differing Watering Regimes

Because of the financial constraints on the numbers of analyses that could be carried out, not all of the plants from this experiment were analysed for elemental composition. However, it was considered important to at least get a limited idea of the nature of elemental uptake by the plants, especially as they had been grown in what can be assumed to be a chemically homogeneous growth medium. Table 6.18 indicates the samples chosen for analysis. Table 6.19 shows the elements that were seen to be significantly altered due to the application of different watering regimes (all raw data for the experimental work is provided in Appendix 3). Because there are so many variables it is hard to generalise, but again this is necessary to allow something to be said about the experimental work. Figure 6.37 provides graphical examples of the data from this assessment.

Table 6.18: Plant Samples Chosen for Chemical Analysis from Experiment 4

<i>Pot No</i>	<i>Watering Regime</i>
W2	Wet to optimum
W49	Wet to dry
W26	Wet constant
W15	Dry to wet
W3	•Dry to optimum
W39	Dry constant
W21	Optimum to dry
W8	Optimum to wet
W9	Optimum constant

Table 6.19: Elemental Concentration Variations with Watering Regime

<i>Treatment</i>	<i>Significant Elemental Concentrations</i>	<i>Statistically Significant Differences</i>
Wets high	~Ca, ~Fe, Mn	
Wets low	Cr, Cu, K, Zn, S	Cu, K, Zn, S
Dries high	Cu, K, Pb, Zn, S	Cu, K, ~Pb, Zn, S
Dries low	Cr	
Low under water stresses	Al, Cr, Mn, Na	
No obvious pattern	~Ca, Mg	
Unreliable data	Cd	

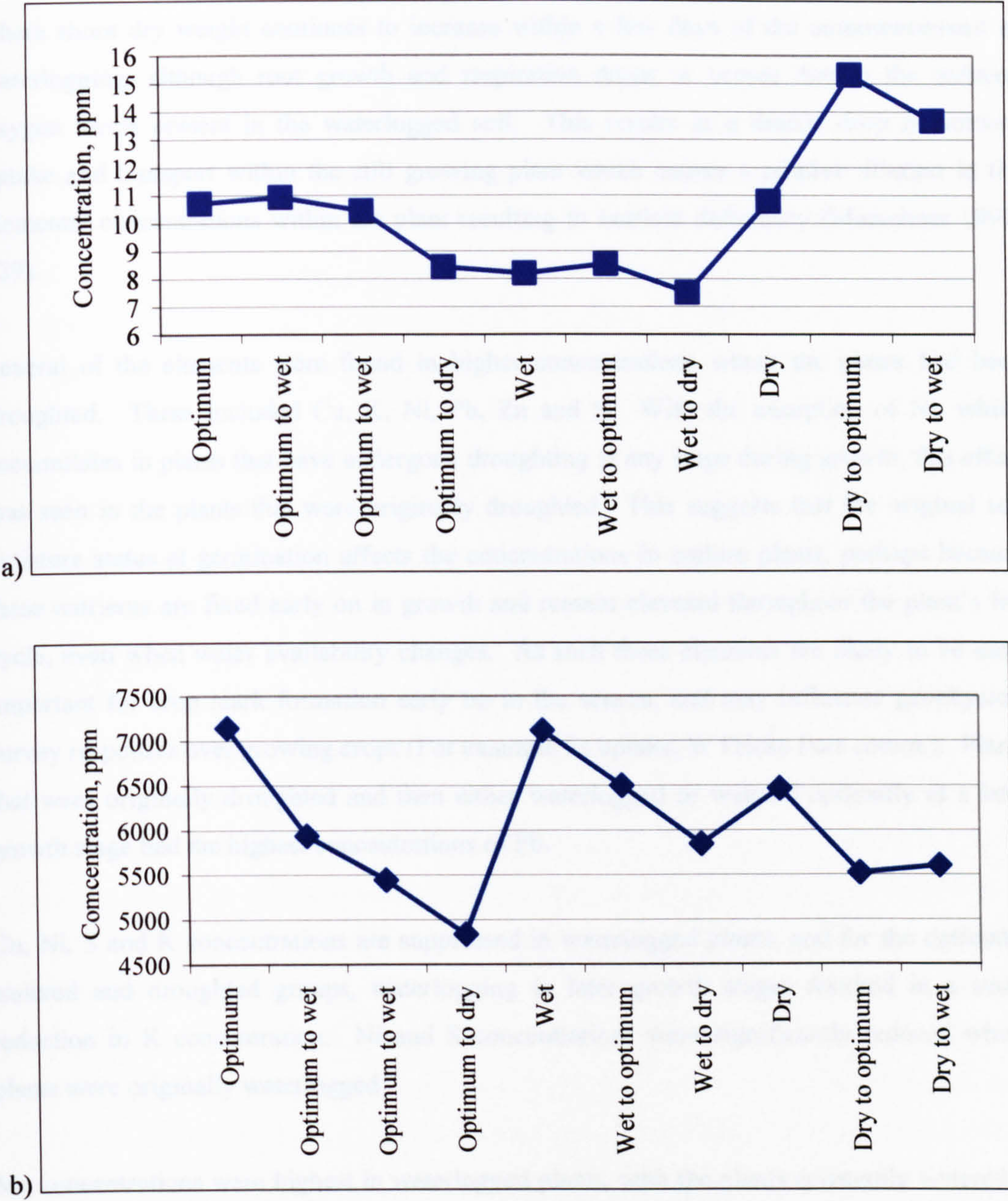


Figure 6.37:
Variations in concentration due to varying watering regimes: a) Cu and b) Ca.

Al, Mn, Cr, Ti and Na concentrations were found to be reduced in any plants that underwent waterlogging or droughting at any stage during their growth, whereas Zn concentrations were decreased in waterlogged plants, and particularly those that grew in originally wet conditions, whilst the concentrations increased where there was droughting. Therefore, uptake of these elements can be said to be linked to water availability, although Cr does not follow this trend. This is likely to be due to a dilution effect, identified in waterlogged plants

where shoot dry weight continues to increase within a few days of the commencement of waterlogging, although root growth and respiration drops or ceases due to the reduced oxygen levels present in the waterlogged soil. This results in a drastic drop in nutrient uptake and transport within the still growing plant which causes a relative dilution in the elemental concentrations within the plant resulting in nutrient deficiency (Marschner 1995, 629).

Several of the elements were found in higher concentrations where the plants had been droughted. These included Cu, K, Ni, Pb, Zn and S. With the exception of Ni, which accumulates in plants that have undergone droughting at any stage during growth, this effect was seen in the plants that were originally droughted. This suggests that the original soil moisture status at germination affects the concentrations in mature plants, perhaps because these nutrients are fixed early on in growth and remain elevated throughout the plant's life cycle, even when water availability changes. As such these elements are likely to be most important for crop mark formation early on in the season, and may influence geophysical survey responses over growing crops (For example Fe uptake, W Fricke Pers comm.). Plants that were originally droughted and then either waterlogged or watered optimally at a later growth stage had the highest concentrations of Pb.

Cu, Ni, S and K concentrations are suppressed in waterlogged plants, and for the optimally watered and droughted groups, waterlogging in later growth stages resulted in a small reduction in K concentration. Ni and S concentrations were significantly reduced where plants were originally waterlogged

Mn concentrations were highest in waterlogged plants, with the plants constantly watered at an optimum rate (effectively the control plants) being the only group to have a higher concentration. Na concentrations tended to increase in any of the plants whose watering regime was changed to optimal during later growth stages, but again all groups were depleted relative to those that were constantly watered optimally. Mo concentrations were increased whenever plants had been waterlogged, no matter what stage of growth this occurred at, with the highest concentrations found where plants were originally waterlogged at the start of the growth season.

Mg, and to a lesser extent Ca, concentrations varied in a non-systematic way, with a trend towards slightly raised concentrations in water-stressed plants, but this was a subtle trend,

which suggests that their uptake is not entirely related to water availability. Ca concentrations were higher when plants had been subject to any of the three watering regimes constantly, with concentrations in waterlogged and optimally grown plants being similarly higher than those that were droughted. Overall Ca was slightly raised generally in plants that had been waterlogged at some stage of growth. Fe concentrations too were highest when optimally watered plants were waterlogged during later growth, suggesting redox potential in the soil affecting Fe uptake in the plants. Apart from this there were few differences in Fe concentrations between the groups.

Discussion of the Results of Experiment 4

This experiment then allows us to say something about water effects on the growth of barley plants. For example in most cases waterlogging plants appears to accelerate growth, but inhibit tiller production, which suggests, and Plates 6.8 and 6.9c confirm that waterlogged plants produce less dense growth. Excess water also stimulates the production of flower heads and encourages taller growth. If the chemical differences associated with these responses can be identified (and this can only be done very superficially in this work, without regard for any of the many biological and biochemical processes and mechanisms involved in producing the differential growth) a start can be made on saying what elements are likely to play a role in crop mark development and whether these elements correlate with those associated with archaeological features in Experiments 2 and 3. In this way an assessment can be made of whether there are certain elements that become enhanced or depleted in soils or plants because of water status, or whether this is an ‘archaeological effect’, or perhaps there are two separate effects, one ‘archaeological’ and one ‘pedalogical’, that exist in tandem to produce the crop mark responses to archaeological sites.

This experiment then answers one of the fundamental questions posed by this thesis: Does differential soil water availability cause growth differences that could be identified as crop marks? The answer to this is clearly yes, for pot based plants grown in proprietary composts, growth differences similar to those observed in crop marks can be produced by varying soil moisture availability. However, the expected and observed outcomes of varying this parameter are set out in Table 6.20, which show that the anticipated growth of droughted and waterlogged plants does not tend to conform to that normally seen in a crop mark. This is not a completely secure comparison however, as droughting and waterlogging are at

extreme ends of the range of SMS/SMD conditions that are likely to be found in a field situation. However, as with the consideration of nutrient status, it represents a starting point. Translated into a field situation, these responses would result in dry or droughted features tending to be interpreted as positive buried features such as cut remains of ditches and pits, where the consensus view is that droughted plants tend to overly compacted layers such as roads and trackways or remains of buildings and other stone-constructed features. The opposite would apply in this case to waterlogged plants, which would be interpreted as overlaying upstanding or compacted features, although under these circumstances the interpretation could be true, with solid remains inhibiting natural drainage in the soil, thus producing waterlogged conditions. Ultimately this experiment shows that the production of crop marks continues to be a complicated affair. The differences in expected and observed responses could be a result of the experimental work not being field-based, as mentioned previously. But assuming that, as has so far appeared to be the case, the pot-based experiments are a reasonable representation of the field situation, another source must be examined in the search for the differences between expected and observed responses. For this reason the nutrient status of these plants was addressed next, and differences in concentrations within the plants were noted. These differences can only be explained in terms of water availability, as this was the only variable in the experimental growth conditions. This dataset then (Table 6.19) represents a series of elements whose concentrations vary in plants grown under optimum conditions but whose watering regimes encompassed optimal, drought and waterlogged conditions. The growth responses recorded are solely a result of these different watering regimes. This information is taken forward to the concluding part of this chapter where it can be used to establish which of the responses are due to differential watering alone, and which are likely to be due to the presence of archaeological remains.

Statistically, the mean elemental differences indicated in Table 6.19 that proved to be significantly different when comparing the means of the concentrations included Cu, K, Zn, S and to a lesser extent (significance = 0.052) Pb. In all cases, droughted plants have the highest concentrations, and waterlogged the lowest, with the exception of Pb, where optimally watered plants have the lowest concentrations rather than waterlogged ones. These decreased concentrations in waterlogged plants and increased concentrations in droughted ones are the most significant of all the changes in concentration due to water availability. These observations suggest consequences for crop mark formation and also present a possible explanation for changes in resistivity responses seasonally, such as those

described by Clark (1990, 53-4). These statistically significant differences between means are based on initial watering regime, and when the concentrations are analysed by grouping the plants into the final watering regime, none of the elemental concentrations appear to be significantly different, suggesting that any differences in elemental uptake is governed by the original watering regime, rather than any SMD/SMS situations that arise later in the growth cycle of the plants (Appendix 3 and 5).

Table 6.20: Expected and Observed Growth Patterns Under Differential Soil Moisture Conditions

<i>Water Regime</i>	<i>Expected Outcome</i>	<i>Observed Outcome</i>
Optimal	Lush green, tall dense 'positive' growth	Lush green, tall dense growth
Dry to Droughted	Stunted light green, less dense 'negative' growth	Stunted very dark reasonably dense growth
Wet to Waterlogged	No real established convention, but tendency to expect 'positive' growth and darker foliage	Sparse tall light green growth, maturing early

6.6 Experiment 5: Effects of Soil Depth Variations and Water Availability on the Growth and Development of Spring Barley

This final experiment brings another variable into the equation. It allows an examination of the effects of different soil depths upon growth, and at the same time allows for changes in water availability to be considered. Experimental details are given in Chapter 3, but the combination of different soil depths and watering regimes allow a number of variables to be looked at within the one growth experiment. First a comparison can be made between optimally watered plants grown at various soil depths, which can be used to compare data for optimally watered plants from Experiments 3 and 4, broadening the continuum of results from these experiments. Second, this experiment allows the field observations made by Jones and Evans (1975, see Chapter 2) to be tested empirically. In addition to this the combined effects of soil depth and water supply can be investigated. Table 6.21 lists the experimental set-up.

Results

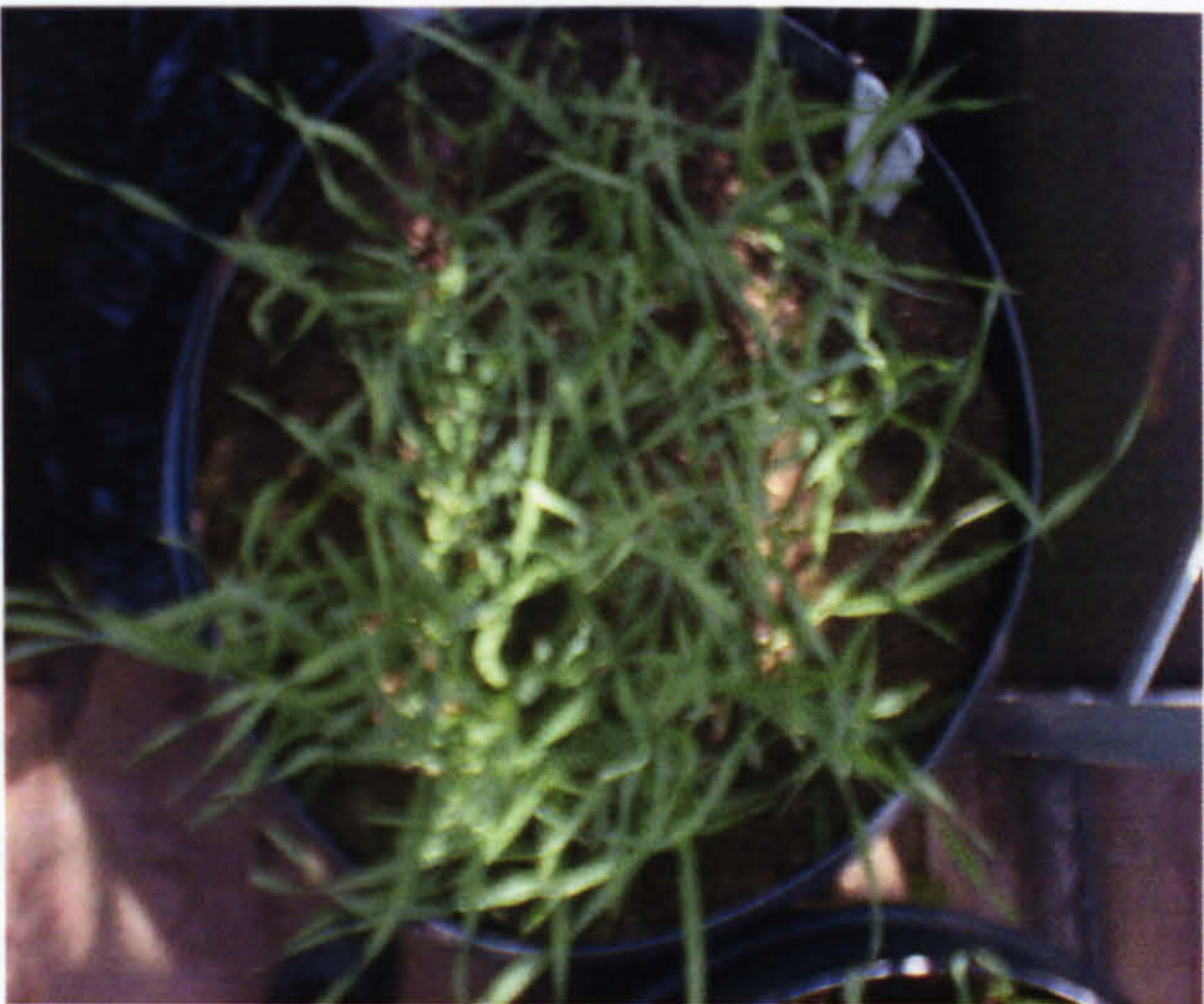
At harvest each treatment was assessed visually and photographed. Because of the dense growth in the containers it was not practical to treat each plant individually as detangling the leaves of each individual was impossible without breakages and therefore inaccuracies in quantitative analysis. Table 6.22 lists the first of the quantitative results for each pot, and the results of the visual assessment follow. Plate 6.10 shows early growth differences in the plants grown in various compost depths and under the differing soil moisture regimes.

Table 6.21: Set Up for Experiment 5

Pot No	Soil Depth and Watering Regime
1	Deep; optimum
2	Shallow; waterlogged
3	Shallow; droughted
4	Medium; optimum
5	Medium; waterlogged
6	Deep; waterlogged
7	Shallow; optimum
8	Deep; droughted
9	Medium; droughted

Table 6.22: Progress of Growth versus Treatment

Pot No	No of Seeds Germinated		Flowers Present	
	15 May 2000	17 May 2000	16 June 2000	19 June 2000
1	74	105	Y	Y
2	133	157	Y	Y
3	84	108	N	Y
4	114	135	N	Y
5	81	113	N	Y
6	84	149	N	Y (few)
7	71	94	N	N
8	71	105	N	Y (few)
9	92	130	Y	Y



a) Deep, dry soil (Pot 8)



b) Shallow optimally watered soil (Pot 7)



c) Deep, wet soil (Pot 6)

Plate 6.10:
Growth differences in Experiment 5 plants.

Pot Number 1

The maximum soil depth (60 cm) for the plants to grow in, and optimal water availability produced lush green foliage that obscured most of the top of the container from sight. Apart from the less than 1% of the basal foliage that had died at the time the plants were harvested, they were a uniform green from the basal leaves to the flower heads (Plate 6.11a). Growth was measured from the floor to the tips of the tallest plants for all the treatments, and in this case reached a maximum average height of c.153 cm (Figure 6.34). The roots of these plants had grown evenly throughout the gravel below the compost (Plate 6.11b), with a small number of roots penetrating through the drainage holes at the base of the container. A number of small patches of orange sandy material were noted in the gravel, usually associated with concentrations of roots.



Plate 6.11:
Pot number 1.

Pot Number 2

The extent of the shallow soil depth treatments, these plants were dwarfed during growth. The treatment produced very growth with a very stunted, dark blue-green appearance, with reduced basal foliage obscuring the top of the pot (Plate 6.12a). The maximum density

Pot Number 2

These waterlogged plants were grown in 20 cm of compost and produced mid- to light-green foliage with very little basal cover (Plate 6.12a), of which around 50% had died, leaving the top of the pot completely visible. These plants reached a maximum height of *c.*140 cm from the ground. Compared to pot number 3, the second of the shallow compost treatments, these waterlogged plants produced a larger number of roots, which like those in pot 3, had penetrated the gravel (Plate 6.12b). The roots appeared to be stabilising the gravel more at its interface with the compost compared to other treatments, where the gravel spilled out of the container when it was opened to inspect root growth.



a)



b)

*Plate 6.12:
Pot number2.*

Pot Number 3

The second of the shallow soil depth treatments, these plants were droughted during growth. This treatment produced top growth with a very stunted, dark blue-green appearance, with minimal basal foliage covering the top of the pot (Plate 6.13a). The maximum average

height of the plants was around 117 cm from the floor. There were very few dead or yellowing leaves. Traditionally, based on the colour of the foliage, this would be interpreted as a positive crop mark from the air. This has implications for the interpretations placed upon features recorded as darker green growth, which tend to be classified as overlying cut features rather than the shallow depths involved here. However, as Experiment 4 results indicate, this is more likely to be a function of water availability than of soil depth. The roots were growing into the underlying gravel as Plate 6.13b shows, suggesting that root extension does not end where nutrient-rich soils terminate, but instead continues into relatively sterile media underlying soils.

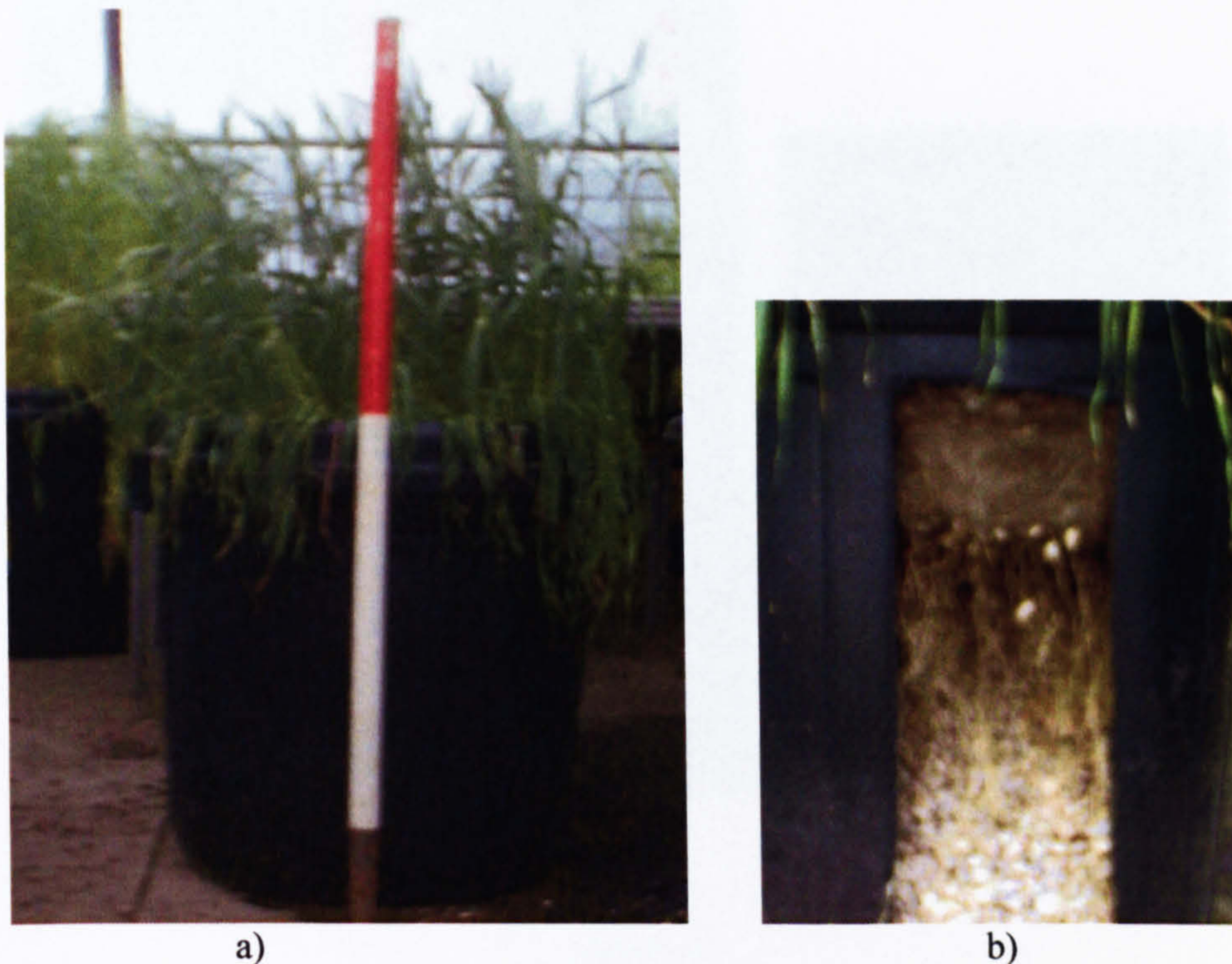


Plate 6.13:
Pot number 3.

Pot Number 4

These plants were grown at what would effectively be the control conditions, that is a medium 40 cm soil depth coupled with an optimum watering regime. This produced a dense canopy of dark green foliage with few dead leaves. The basal leaves obscured the top of the container and the total maximum height from the floor to the tip of the tallest glumes

measured around 149 cm (Figure 6.34; Plate 6.14a)). The roots extended around 10 cm into the gravel below the compost. Despite the root ball not being very dense (Plate 6.14b), when the pot was emptied out it was found that the roots had penetrated throughout the depth of the gravel and were growing out of the basal drainage holes of the container.

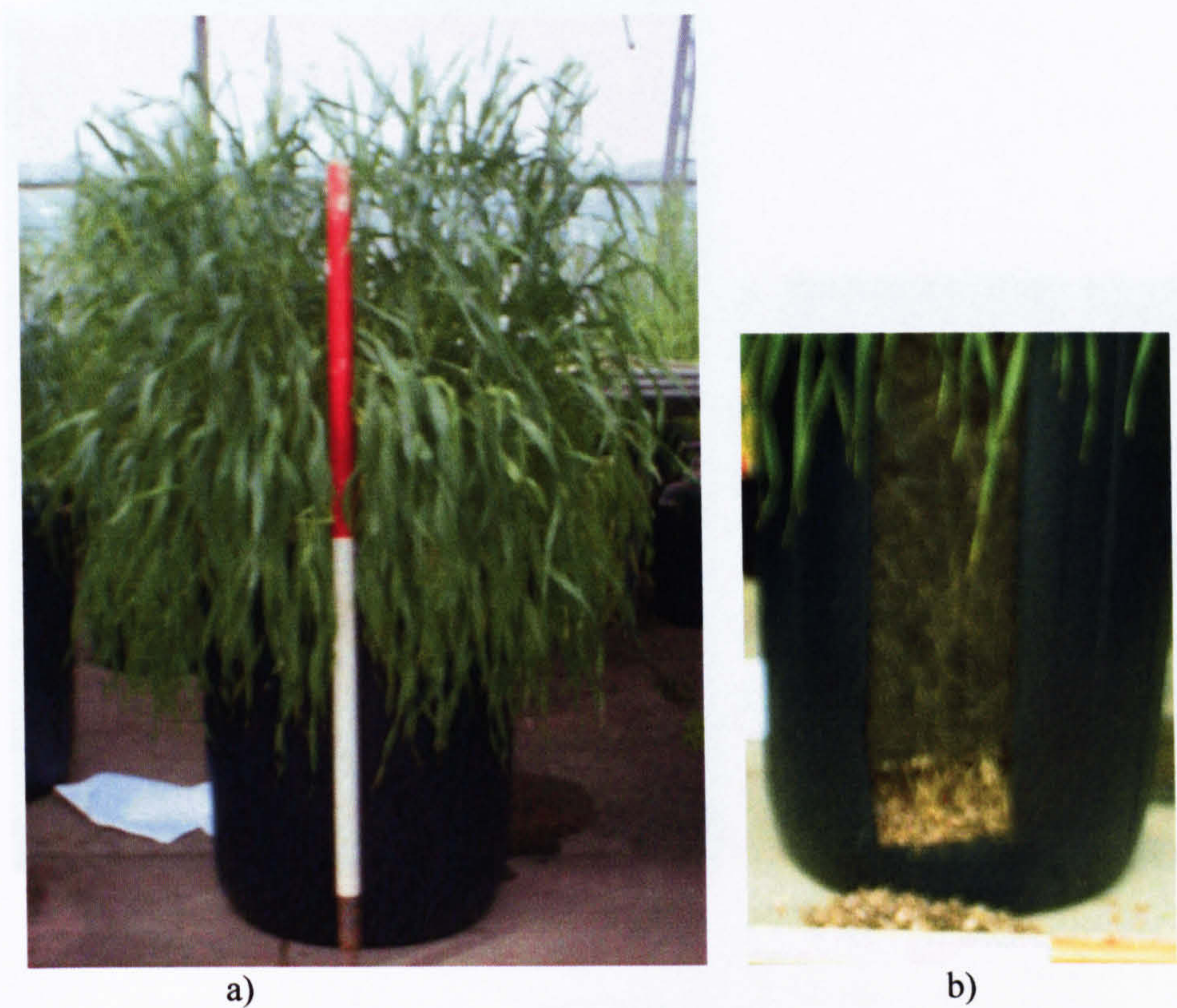


Plate 6.14:
Pot number 4.

Pot Number 5

This container also had a medium compost depth, but this time the plants growing in it had been waterlogged. The foliage produced was mid-green in colour, with around 45% of the basal leaves having died and the full complement not being dense enough to cover the top of the container (Plate 6.15a). The maximum height of growth from the floor was around 144 cm. The roots extended through the gravel with the densest concentration of roots within the

top 10 cm of the compost (Plate 6.15b), and some, although not as many as in pot number 4, had penetrated through the drainage holes.

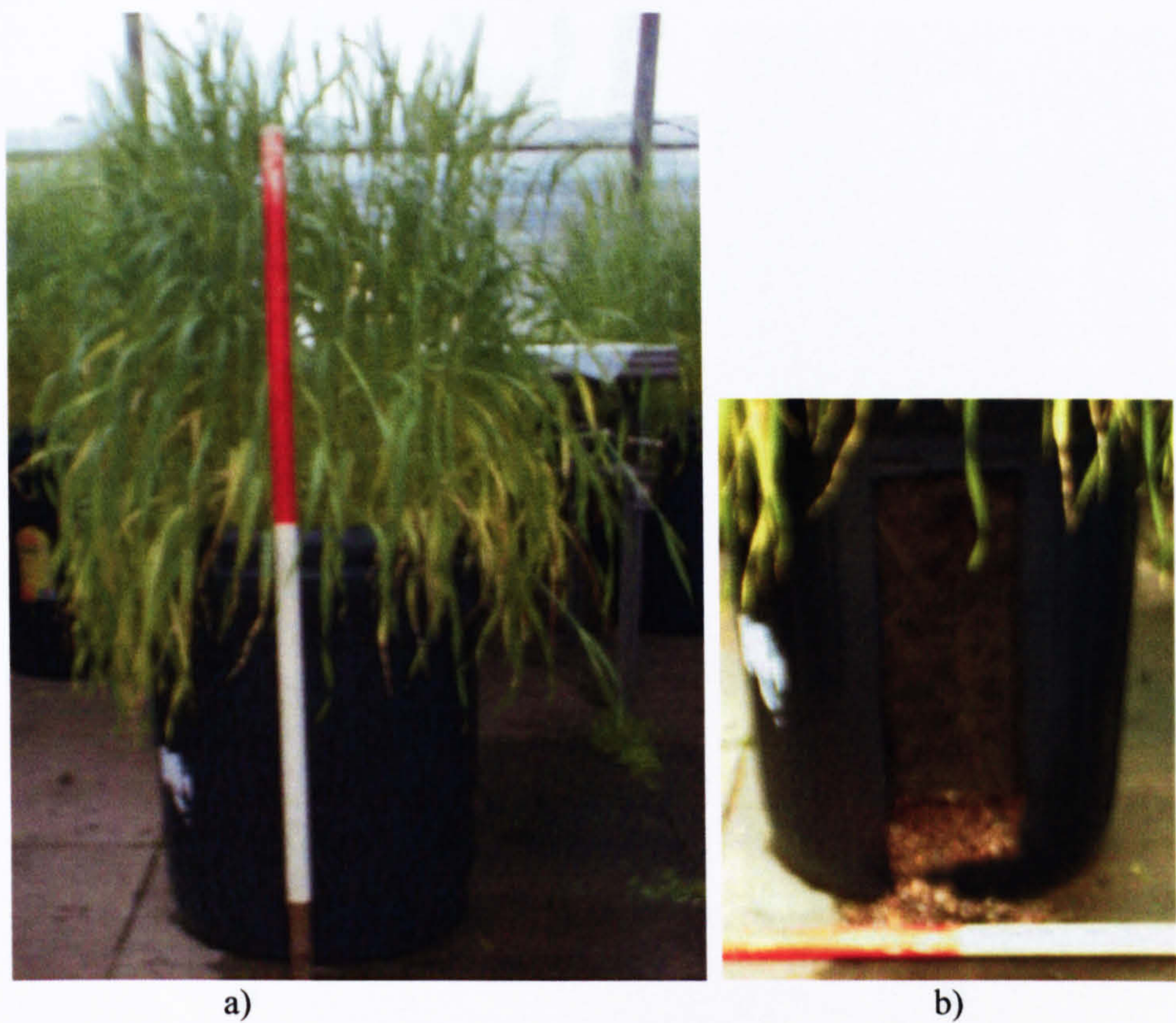


Plate 6.15:
Pot number 5

Pot Number 6

This was the second of the three treatments containing the maximum 60 cm of compost, and the plants were waterlogged. This treatment produced a sparse leaf cover which was dark green at the tops but paler green in the lower half of the plants (Plate 6.16a), evidence of nutrient deficiency, for example Mg, which is not enhanced in waterlogged plants compared to many of the other nutrients (Table 6.25; Bould *et al* 1983, 62). In addition around 50% of the basal leaves were either dead or dying and there was only around 45% coverage of the top of the container. The plants had reached a maximum height of around 145 cm. Roots

were present in the gravel (Plate 6.16b), as with all of the treatments, and when the container was opened up water seeped out of the gravel part of the fill.

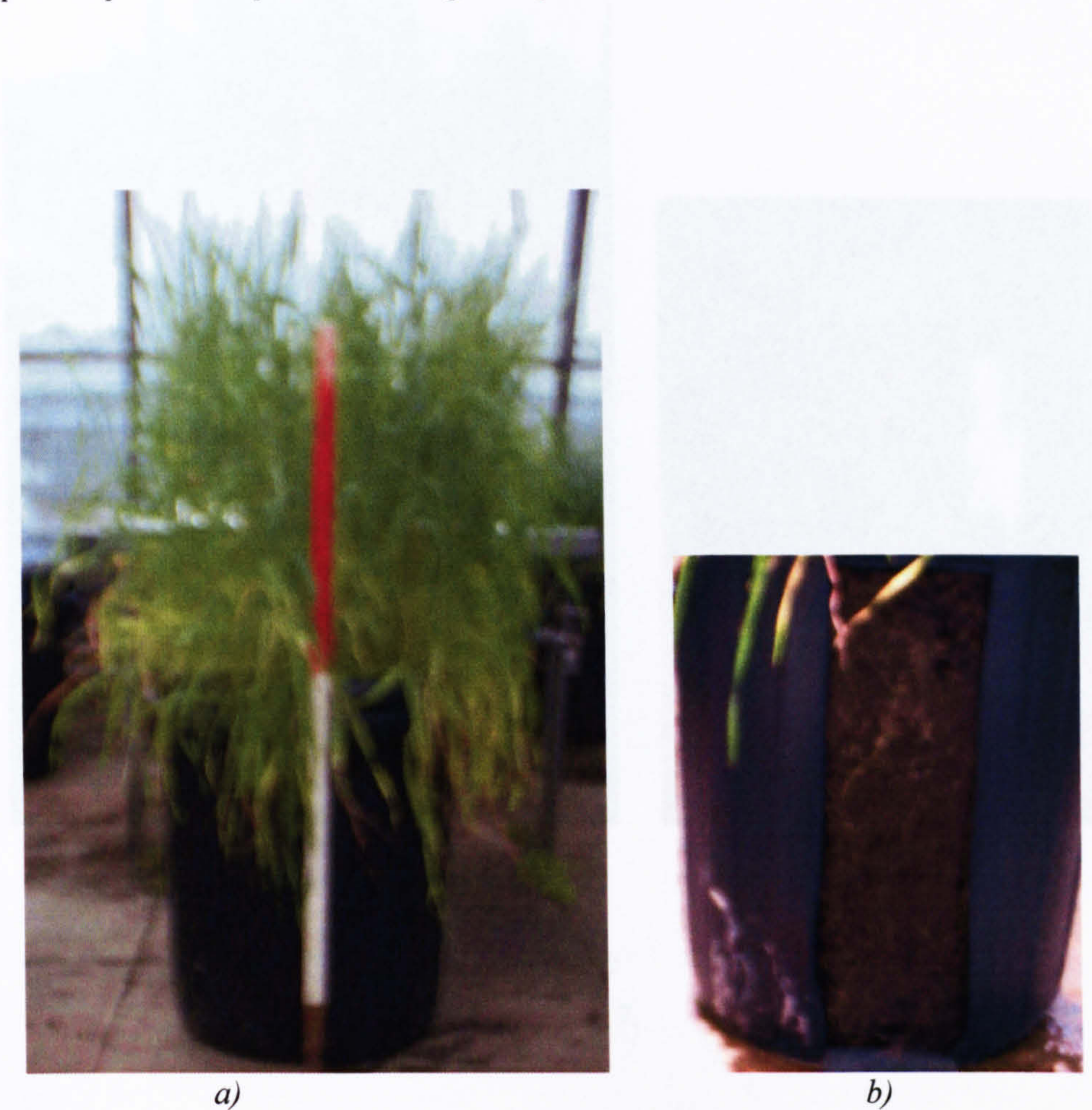


Plate 6.16:
Pot number 6.

Pot Number 7

This was the last of the three shallow soil treatments, and in this case the plants were watered optimally. These plants produced uniformly coloured mid- to dark-green foliage with a small number (*c.* 5%) of dead leaves at the base (Plate 6.17a). The basal leaves covered most of the top of the container. The plants grew to a maximum height of around 145 cm and produced a high number of roots (Plate 6.17b), most of which were concentrated towards the bottom of the pot, in the gravel.

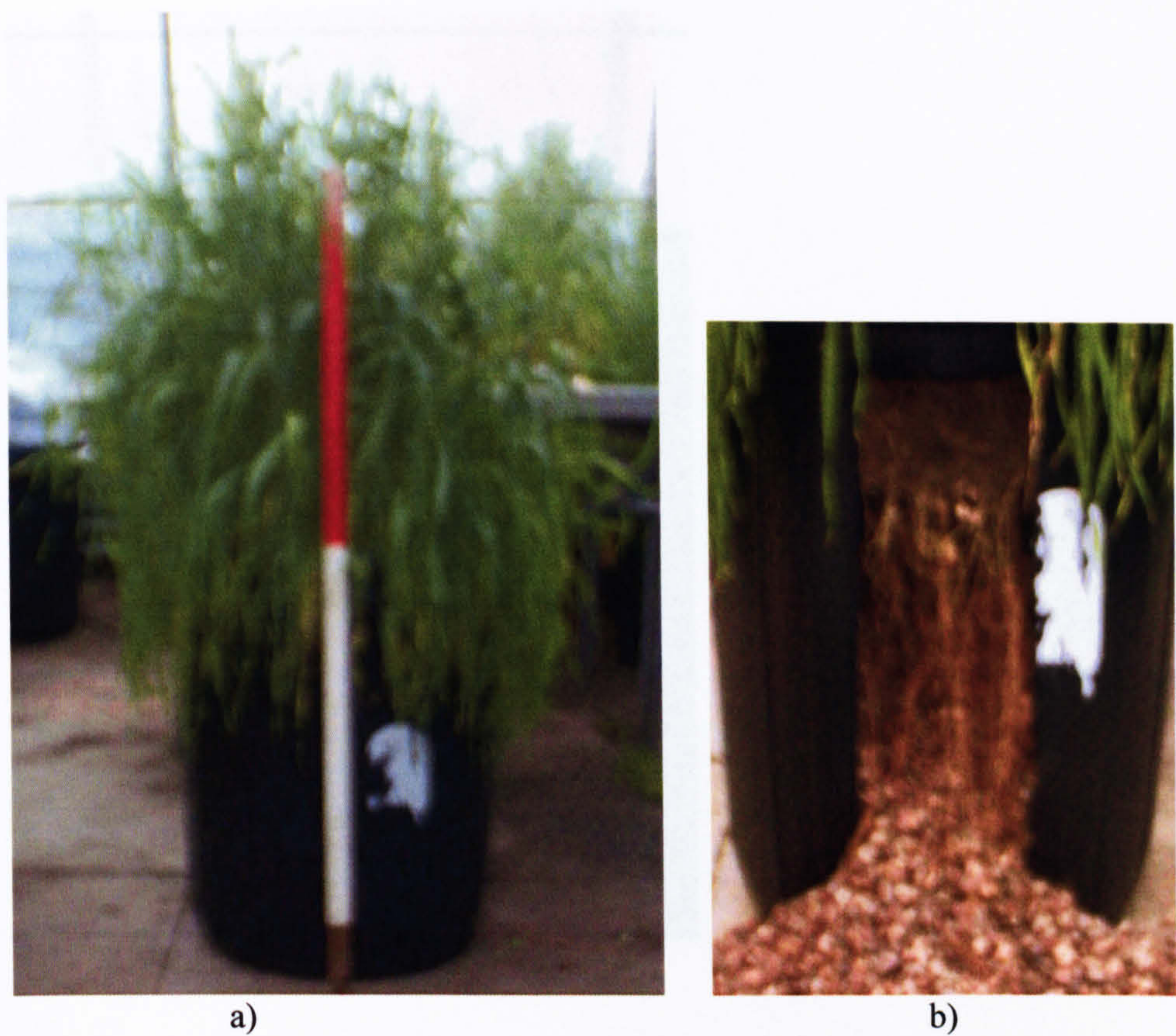


Plate 6.17:
Pot number 7.

Pot Number 8

This contained the third deep soil fill and the plants in it were droughted. This treatment produced lush, dense growth which was a uniform mid- to dark-green in colour with very few dead basal leaves (only one yellow leaf was visible at harvest; Plate 6.18a). The growth produced reached a maximum height of 138 cm from the ground. Despite the roots penetrating through the compost and gravel, the distribution of roots generally was much less obvious in this treatment than in the other 8 containers (Plate 6.18b).

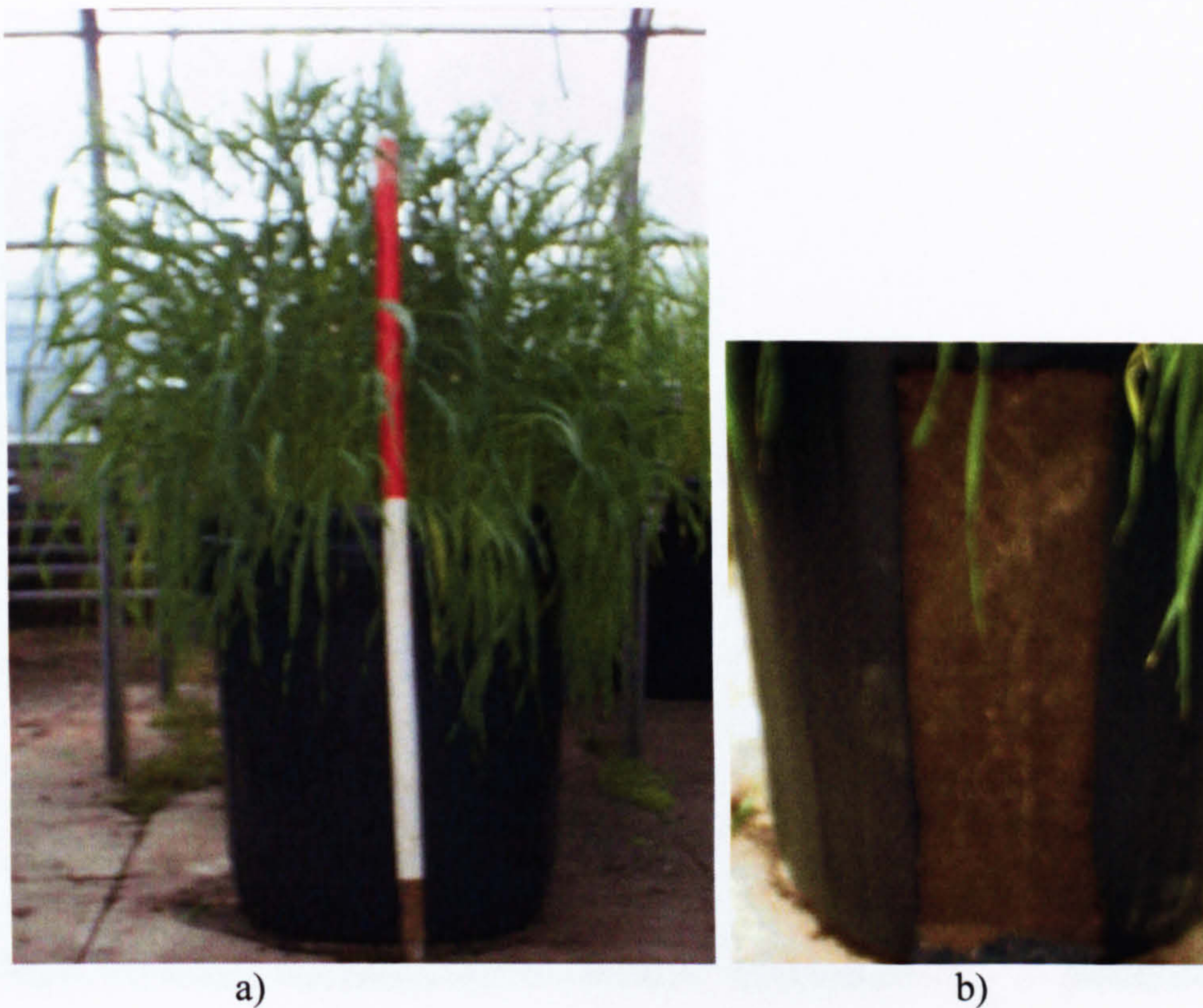


Plate 6.18:
Pot number 8.

Pot Number 9

In the last container the medium depth of compost and droughted plants produced dark green stunted growth with flower stems appearing a blue-green colour (Plate 6.19a). Of the 40% coverage of the top of the pot by the basal leaves, *c.*50% were dead or dying. The plants reached a maximum height of *c.*125 cm. The roots had penetrated into the gravel and, as with Treatment 1, orange patches associated with the roots were visible in the gravel, but in this case only two patches were noted (Plate 6.19b).

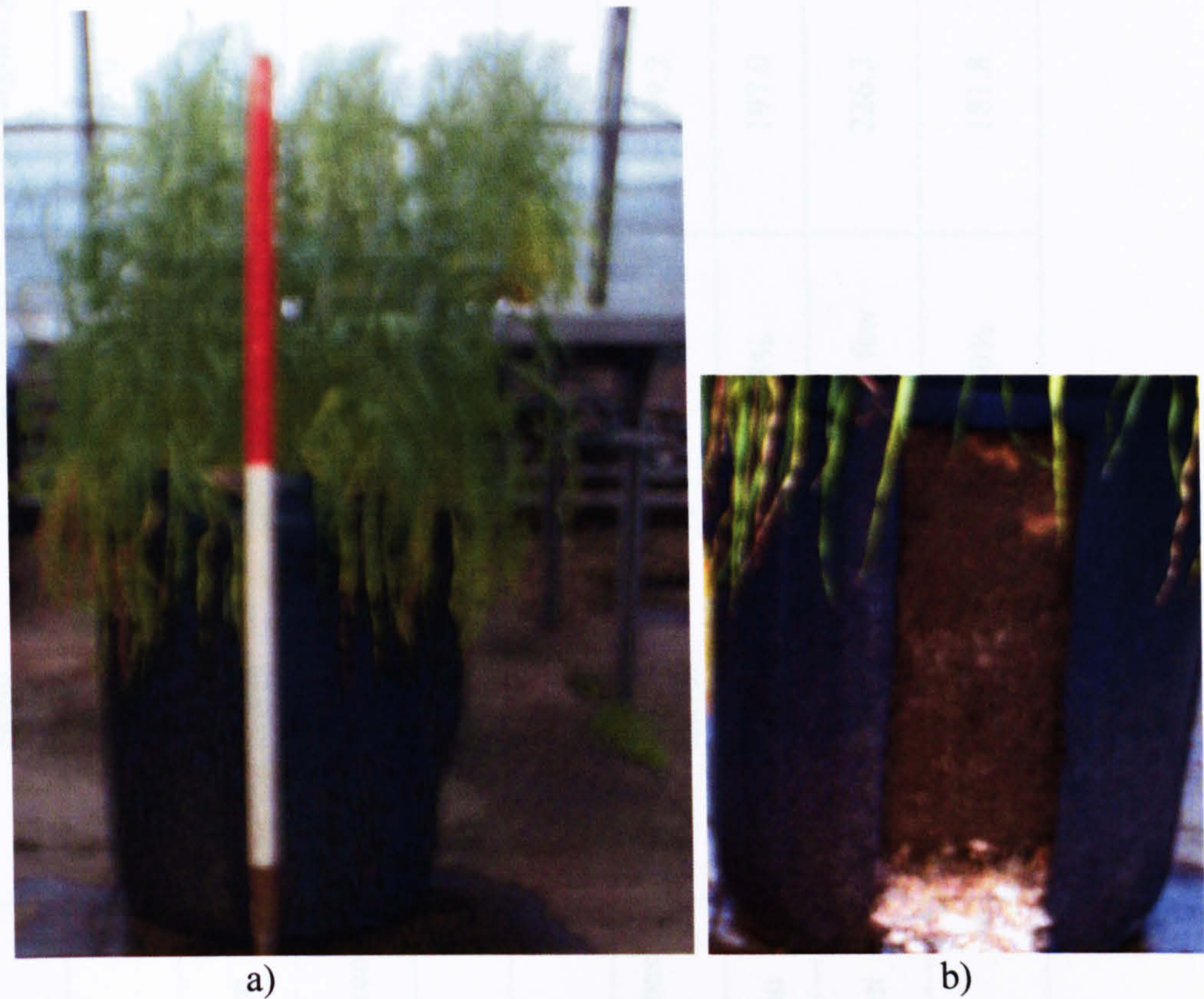


Plate 6.19:
Pot number 9.

The plates accompanying the descriptions of the individual treatments show that very obvious differences exist between these plants. Table 6.23 summarises the information and gives further measurements from the harvest of the plants.

Table 6.23: Summary of the Growth Habits of Experiment 5 Plants at Harvest

Pot No	Soil Depth	Watering Regime	Colour	Habit	Dead Leaves	Dry Weights, g
1	Deep	Optimum	Lush green	Dense, bushy, uniform	<1%	335.9
2	Shallow	Waterlogged	Mid to light-green	Sparse, thin, few basal leaves	c. 50%	162.9
3	Shallow	Droughted	Very dark blue-green	Stunted, sparse, few basal leaves	few	131.7
4	Medium	Optimum	Dark green	Dense, bushy	few	291.8
5	Medium	Waterlogged	Mid green	Sparse, thin, few basal leaves	c. 45%	195.9
6	Deep	Waterlogged	Dark green, lighter basal portion	Sparse, thin, few basal leaves	c. 50%	189.2
7	Shallow	Optimum	Mid to dark-green	Dense, uniform	c. 5%	197.0
8	Deep	Droughted	Mid to dark-green	Dense, lush, uniform	Very few	226.3
9	Medium	Droughted	Dark green	Stunted, sparse, few basal leaves	c. 50%	181.8

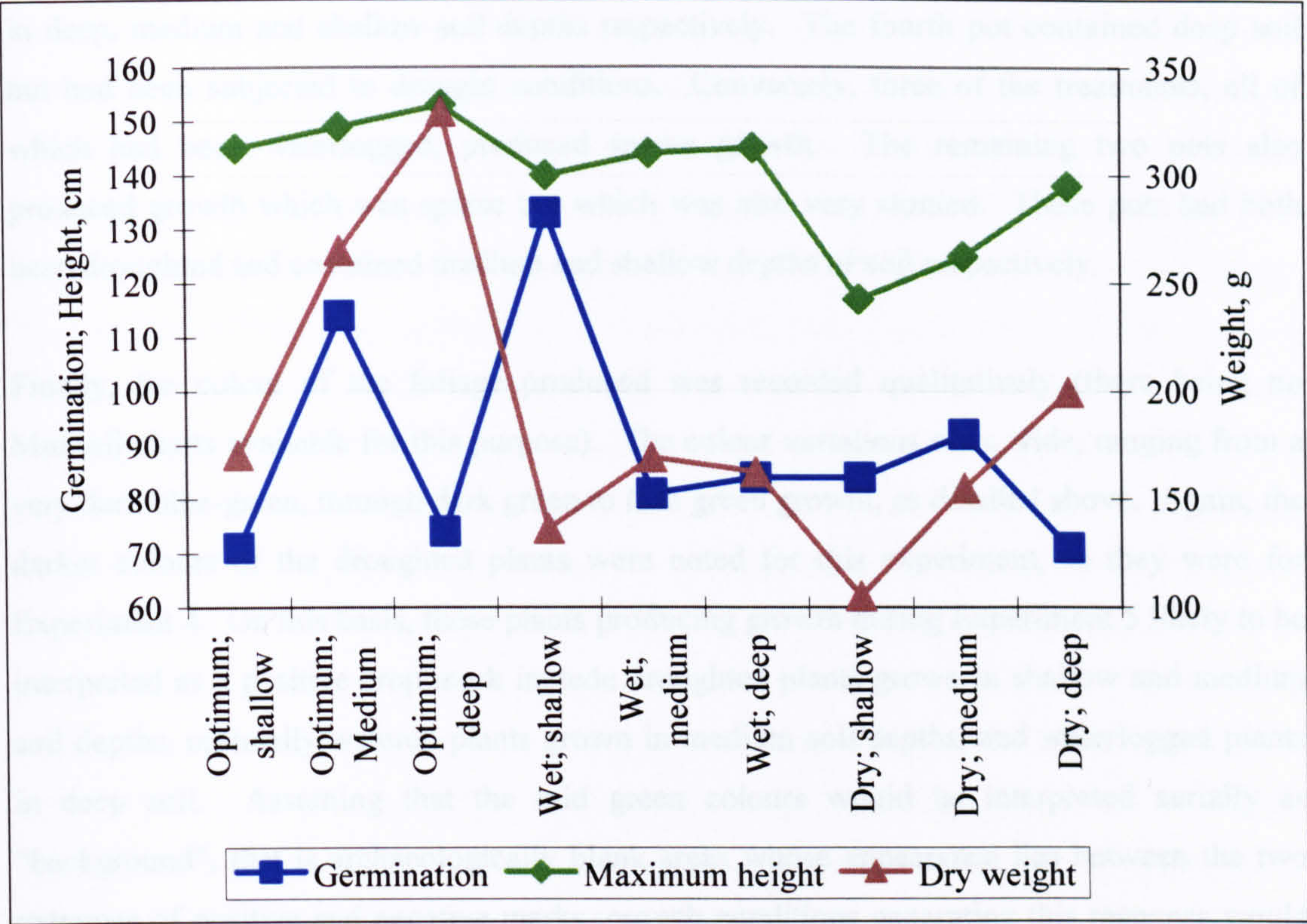


Figure 6.38:
Germination rate after one week, maximum heights and dry weights for plants grown in Experiment 5.

From Table 6.23 and Figure 6.38 it is clear that there were quite marked differences in the appearance of the plants grown under the individual cultural regimes (Plates 6.11 to 6.19). Taking germination rates first, no significant patterns were seen in germination rates relative to either soil depth or watering regime, although for optimally watered and droughted groups the medium soil depths supported the highest germination rates. Plant height was most affected by watering regime. Optimally watered plants were the tallest, and droughted plants were always the shortest and for each watering regime, increased heights correlated with increased soil depth. The dry weights followed the same, but much more pronounced, trend as that observed for plant heights. The exception to this pattern was noted for the waterlogged plants, where the dry weight decreased slightly for the plants grown in the deepest soil.

The final qualitative assessment of this experiment involved examining the foraging plants in

Growth habit, which reflected density of leaves and number of tillers, and thus the average ground cover that would be seen aurally, was assessed visually and is described above. Four of the treatments resulted in dense growth, three of which were watered optimally, but grown

in deep, medium and shallow soil depths respectively. The fourth pot contained deep soil but had been subjected to drought conditions. Conversely, three of the treatments, all of which had been waterlogged, produced sparse growth. The remaining two pots also produced growth which was sparse but which was also very stunted. These pots had both been droughted and contained medium and shallow depths of soil respectively.

Finally, the colour of the foliage produced was recorded qualitatively (there being no Munsell charts available for this purpose). The colour variations were wide, ranging from a very dark blue-green, through dark green to lush green growth, as detailed above. Again, the darker colours of the droughted plants were noted for this experiment, as they were for Experiment 4. On this basis, those plants producing growth during Experiment 5 likely to be interpreted as a positive crop mark include droughted plants grown in shallow and medium soil depths, optimally watered plants grown in medium soil depths, and waterlogged plants in deep soil. Assuming that the mid green colours would be interpreted aurally as “background”, that is archaeologically blank areas whose appearance lies between the two extremes of positive and negative marks, growth conditions generating this response would include optimally watered plants grown in deep and shallow soil depths, waterlogged plants in medium soil depth and droughted plants in deep soils. The only cultural conditions producing growth of a relatively lighter colour such as would be interpreted as a negative crop marks, were noted in plants that had been grown in shallow soils and waterlogged. As crop marks are interpreted on the basis of density of growth as well as colour, this characteristic would result in the dense growth of optimally watered plants of all three depths and droughted plants growing in deep soils to be interpreted as positive marks, while all of the waterlogged and the shallow and medium soil depth droughted plants would be interpreted as negative marks. Combining the two characteristics of colour and density of growth results in optimally watered plants grown in medium depths of soil producing characteristic positive crop mark growth, and shallow depths of soil experiencing waterlogging producing characteristic negative growth. In the concluding part of this chapter the implications for aerial photographic interpretation based upon these results is considered further.

The final qualitative assessment of this experiment involved examining the barley plants in groups based firstly upon watering regime, and then on soil depth. These groups are illustrated in Plates 6.20 to 6.21. Plate 6.20a shows the optimally watered plants grown in, from left to right, shallow, medium and deep soils. These plants display little variation in

growth habit, despite being grown in three different soil depths. Medium soil depths appear to have produced a denser growth, with the largest number of basal leaves, and the deepest soil has produced the least dense growth, but visually there is little difference between the three, suggesting that when plants are optimally watered, soil depth is not an important factor in development of the plants visually. As with those plants that were watered optimally, there is little difference in the appearance of the plants that were waterlogged and grown in shallow, medium and deep soils respectively (Plate 6.20b). All of the pots contain plants whose growth appears yellow towards the base, with little cover of the tops of the pots by the basal foliage. As with the optimally watered plants, there is little difference in leaf colour within the group. Again, the plants that were droughted have all developed dark green, stunted foliage, with little basal growth (Plate 6.20c). The shallow soil depth appears to have produced the least dense growth, supporting plants with smaller leaf areas than those in the medium and deep soils. The medium soil contains plants with the highest numbers of dead leaves. Growth in the deep soils is much taller than that in the remaining two soil depths, suggesting that for drought conditions, soil depth is an important factor in maintenance of aerial growth in barley (see Chapter 2, and Jones and Evans 1975).

Next the plants were assessed on the basis of soil depth, so that water availability as a factor could be assessed with soil depth being kept constant. As would be expected on the basis of Experiments 3 and 4 the effect of varying water regime was to produce differential growth (Plate 6.21). There are marked differences in the growth patterns from this grouping. While the optimally watered plants exhibit healthy, dense top growth, the waterlogged plants are more upright, less dense, produce fewer tillers and have much dead foliage at their bases. The droughted plants are stunted and very dark green. Clearly water has a major effect on the appearance of these plants grown in shallow soils (Plate 6.21a). The same growth patterns described for the plants grown in shallow soils is apparent in those grown in medium depths (Plate 6.21b), although the differences are less pronounced in the latter, suggesting that although water is a governing factor, the increased soil depths in this group (twice as deep at 40 cm) provide a buffer to the effects of moisture stress, confirming the idea that there is likely to be a reservoir effect in increased soil depths under field conditions. In this case however, the main differences to be seen are in those plants that were waterlogged, with a much more subtle increase in leaf area, height and leaf colour in the optimally watered plants relative to the droughted ones. This confirms that the field observations made by Jones and Evans (1975) are also reproducible in pot-based experiments. The experiment suggests that as soil depths generally increase over a field, the

differences in growth caused by differential water availability such as would traditionally be expected at a crop mark site are likely to be reduced due to the buffering effect of the increased topsoil depths (Plate 6.21c). It does not confirm however, that crop mark formation occurs in response to a change of soil depth alone, for example over a deeply cut ditch relative to the surrounding undisturbed ground, if all other factors are equal. The results indicate that water is a significant factor in the development of differential growth in barley, far more so than soil depth, and without changes in moisture availability together with depth changes the crop marks above cut features are unlikely to develop.

Taking this to an extreme, Plate 6.22 shows the visual differences produced in what would be regarded as a typical archaeological situation. The individual pots (Plate 6.22a) represent the situation that would hypothetically occur at a site containing a shallow soil depth due to the presence of building foundations or similarly compacted feature (shallow soil, droughted plants), a ditch feature (deep soil; waterlogged plants) and an undisturbed soil between the two (medium depth, optimally watered). This is not the traditionally expected response to the features described above. A response that more closely represents those recorded aerially in Britain are achieved using waterlogged plants in shallow soils to represent the positive (e.g. building remains), and optimally watered plants grown in deep soils to represent the negative (cut) features, as can be seen in Figure 6.22b. When waterlogged shallow plants are substituted for the droughted ones and optimally watered rather than waterlogged plants grown in deep soils we approach the observed norm for crop mark formation. This suggests one of two things, particularly when considering the shallow soil depths. Either the effects of buried archaeological remains differs from that traditionally described for positive features, or negative crop marks appearing above such features, according to this experiment, appear in response to waterlogging rather than droughting. If this is *not* the case, the experimental work suggests that although water does have a role in the changing growth patterns, there is another factor at play too. As soil depth has been ruled out as a major influence on crop mark development during this final investigation, the only variable that remains is soil chemistry. This is particularly the case if we consider the geophysical responses to archaeological sites, and this is discussed in the conclusions to this chapter. This last variable is addressed by looking at ICP-MS analysis results for a sample of plant material taken from each of the 9 pots.



Plate 6.20a:
Optimally watered plants from Experiment 5.



Plate 6.20b:
Waterlogged plants from Experiment 5.



Plate 6.20c:
Droughted plants from experiment 5.



a: Plants grown in Shallow soils



b: Plants grown in medium soil depths



c: Plants grown in deep soils

Plate 6.21:

Effects of changing water regimes on plants from the same depths of soils (all from left to right waterlogged, droughted, optimum).



a): the traditional interpretation: shallow droughted plants; medium soil and optimal water supply and deep wet soil



b): Treatments chosen to fit the traditionally expected crop mark response

Plate 6.22:

Hypothetical development of crop marks.

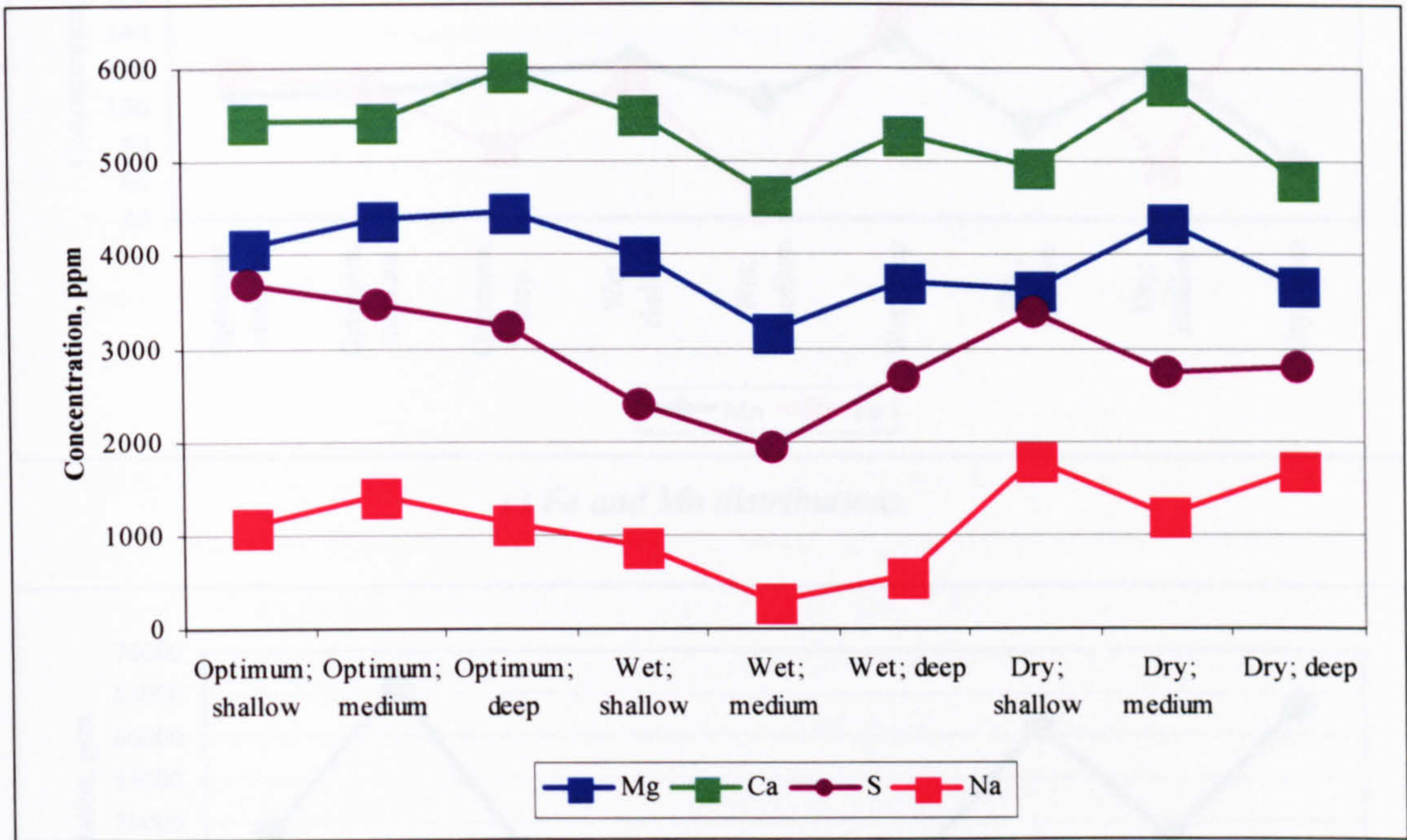
Results of the Plant Analyses from Experiment 5

In this experiment it is again assumed that all nutrient concentrations in the proprietary compost were the same for each pot and so any differences in the plant analyses can be assumed to be due to either a larger soil volume or altered water availability. First the data was assessed by producing graphs of concentrations of elements grouped by soil depths, to determine whether this factor is indeed as insignificant a factor as the qualitative analysis

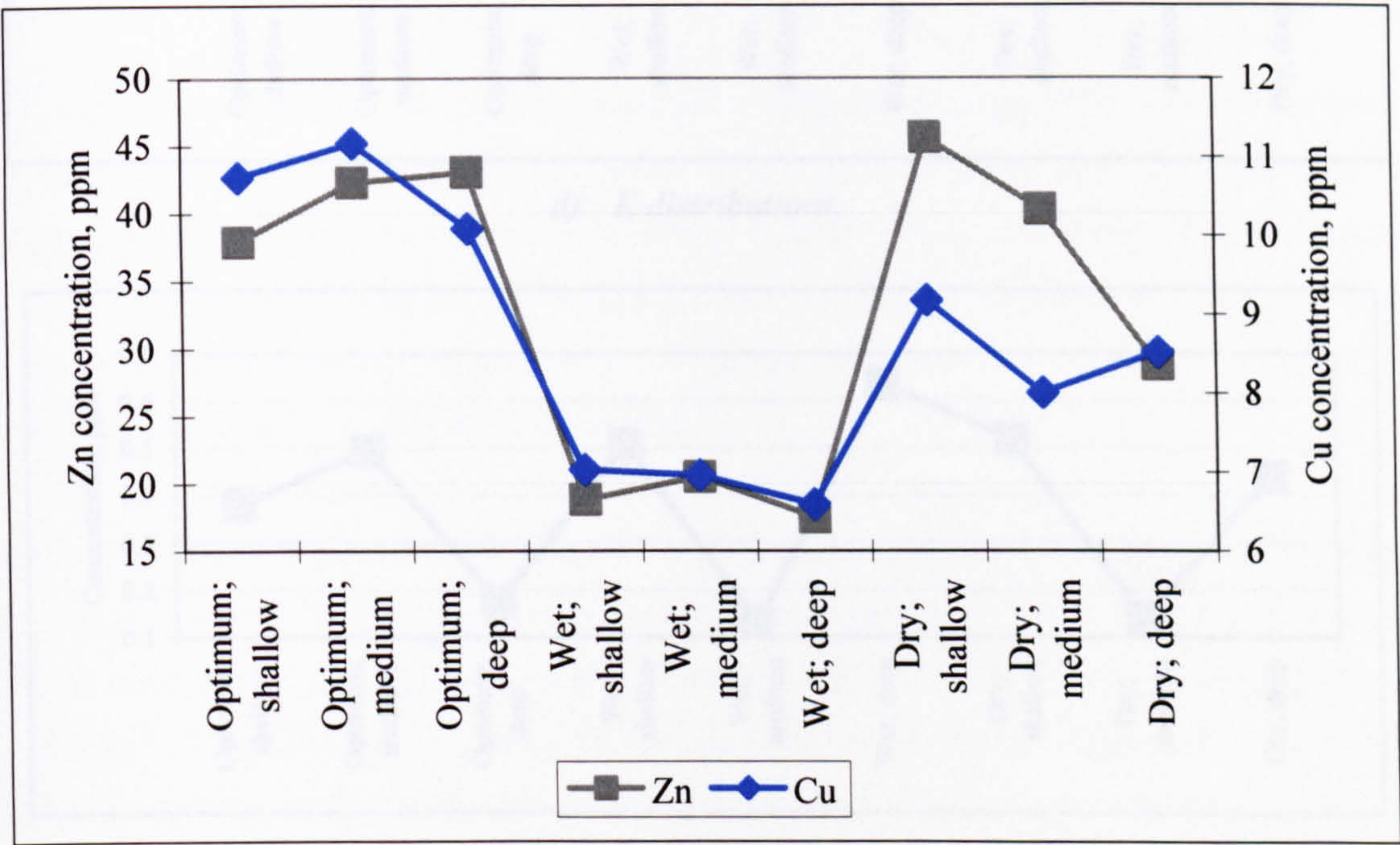
made in the preceding section suggests. From the dataset, analyses that were considered to be unreliable included Cd, Co, Mo, Ni, P and Ti. Of the remaining elements a high proportion failed to reveal any significant patterns based on changing soil depths, tending to confirm the conclusions made previously. Of the 17 elemental concentrations analysed only four (S, Cr, Fe and K, Figure 6.39) revealed patterns that indicate differential uptake depending on soil depth. S concentrations (Figure 6.39a) were enhanced in plants grown in shallow soils when they had been either watered optimally or droughted. For Cr (Figure 6.39e) and Fe (Figure 6.39c) all water-stressed plants grown in medium soil depths had lower concentrations. Optimally watered plants grown in deep soils also displayed depressed concentrations of Cr and Fe. For K (Figure 6.39a) the waterlogged plants had the lowest concentrations. In the optimally watered and droughted plants the concentrations varied in a similar but inverse way, with droughted plants having high concentrations in shallow and deep soils and low concentrations in medium soils, and optimally watered plants, the reverse. The remaining elements showed a similar distribution pattern (see Figure 6.39) with optimally watered and droughted plants having higher concentrations than waterlogged ones generally. Although the variations associated with soil depth were noted only in a small number of elements, it is significant that Fe is one of them.

Statistically the only element that exhibited significant changes in concentration with soil depth was Fe, with highest concentrations found in plants growing in deep soil, closely followed by those in shallow soil depths, with relatively depleted concentrations in plants grown in medium soil depths. This has significant implications for not only magnetic survey data, but on the basis of information received (W Fricke pers comm., see Chapter 2) for aerial reconnaissance results too. Bearing in mind that the soils that these plants were grown in were horticultural composts, it would be unlikely to see such variations due to inhomogeneities in the composts, so it must be assumed that the changing soil depths have caused these differences in uptake in the plants. So, although depth changes do not appear to affect plant growth or development to a significant degree visually, in fact chemically this is not the case. The consequences of this for geophysical survey are discussed below. As this data also encompasses the three watering regimes it was re-examined using only the data for optimally watered plants (Table 6.24) so that as with Experiments 3 and 4 a comparison can be made between these results and those preceding them, including those from Experiment 2. The danger in using this dataset however, lies in it containing only one pot, albeit containing a large number of individual plants, per treatment. In the data produced Cd, Co, P, Pb, Ni

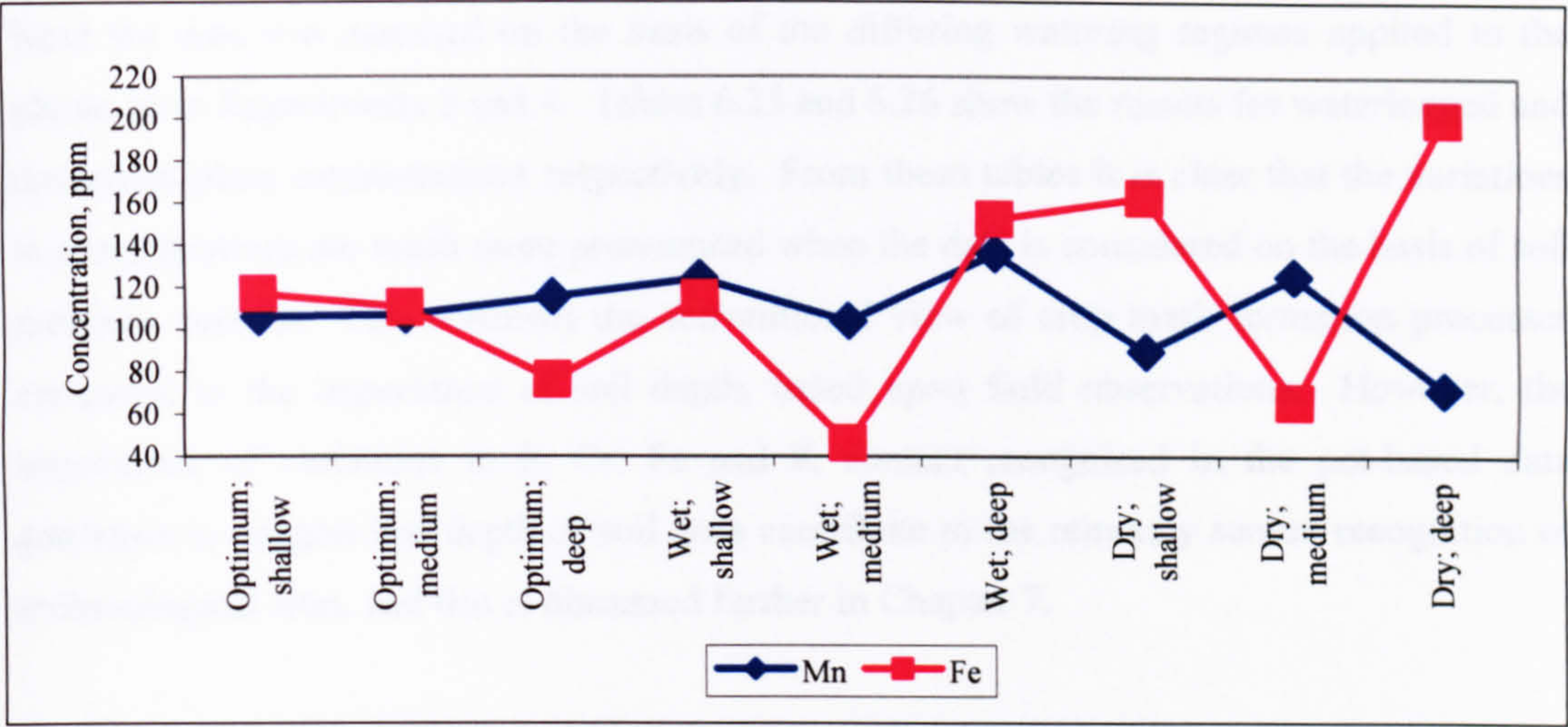
and Ti were considered unreliable, due to contamination of the samples analysed and so these elements are not included in the tables or discussions presented.



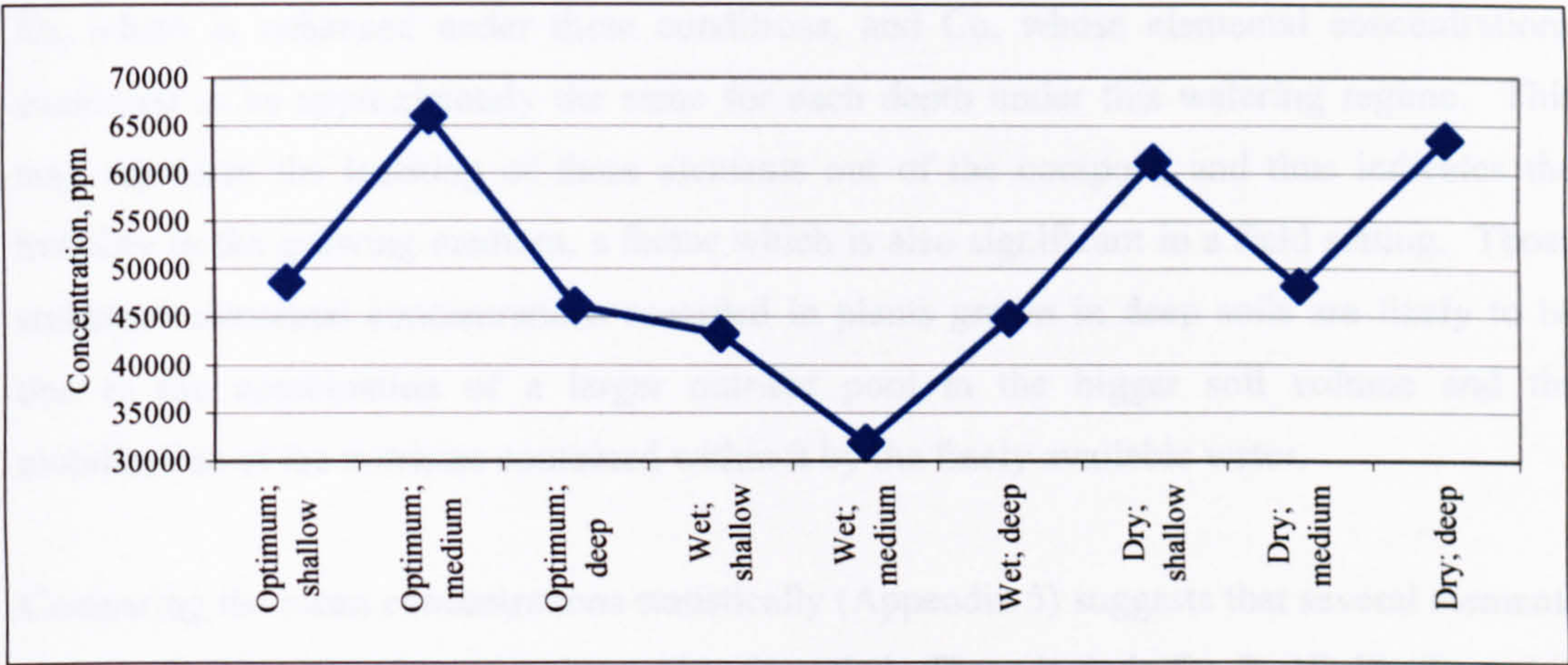
a): Elemental concentrations for Ca, Mg, Na and S.



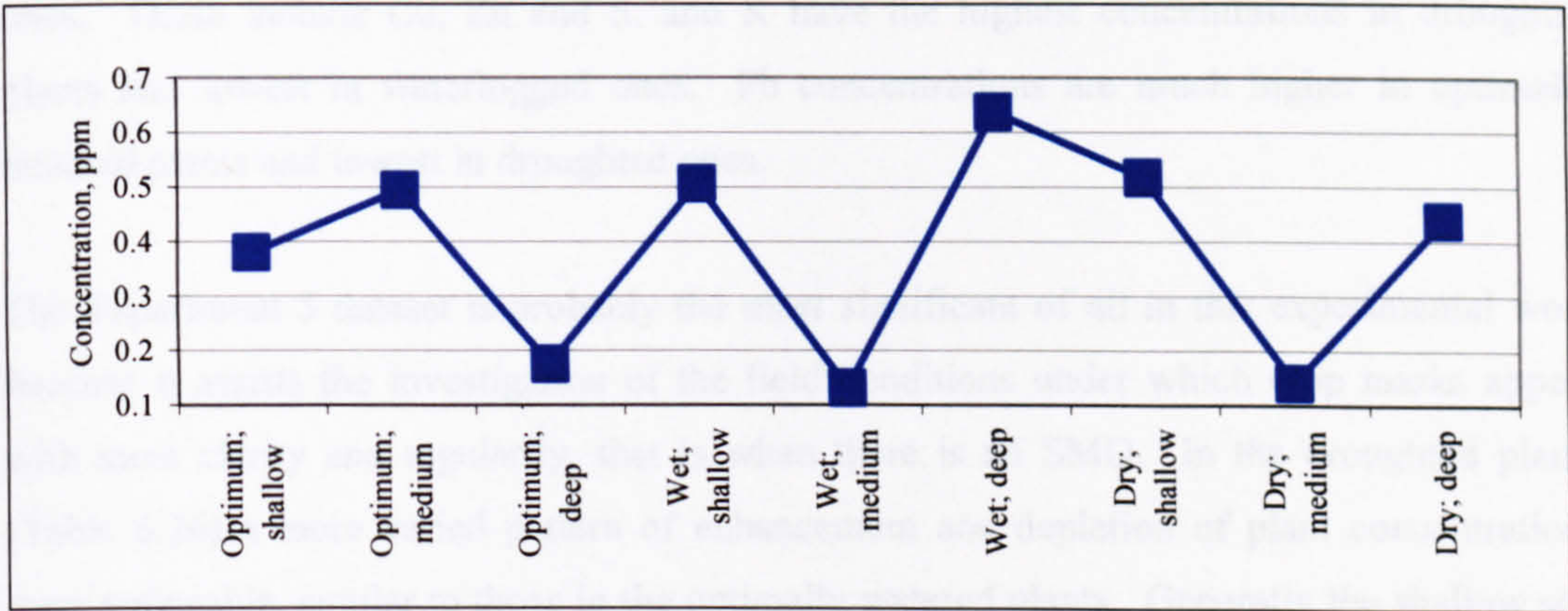
b): Elemental distributions for Zn and Cu.



c) Fe and Mn distributions.



d): K distributions.



e) Cr distributions.

Figure 6.39:
Graphs of concentration of elements in plants from differing soil depths and watering regimes.

Next the data was assessed on the basis of the differing watering regimes applied to the plants, as in Experiments 3 and 4. Tables 6.25 and 6.26 show the results for waterlogged and droughted plant concentrations respectively. From these tables it is clear that the variations in concentrations are much more pronounced when the data is considered on the basis of soil moisture content. This confirms the conventional view of crop mark formation processes compared to the importance of soil depth, based upon field observations. However, the importance of variations in S, Cr, Fe and K content recognised in the pot-based data continues to suggest that depth of soil does contribute to the remotely sensed recognition of archaeological sites, and this is discussed further in Chapter 7.

In plants that were grown under waterlogged conditions the overriding trend is for those grown in medium soil depths to have lower concentrations of elements with the exception of Zn, which is enhanced under these conditions, and Cu, whose elemental concentrations continued to be approximately the same for each depth under this watering regime. This may represent the leaching of these elements out of the compost, and thus indicates the mobility in the growing medium, a factor which is also significant in a field setting. Those enhanced elemental concentrations recorded in plants grown in deep soils are likely to be due to the combination of a larger nutrient pool in the bigger soil volume and the mobilisation of the nutrients contained within it by the freely available water.

Comparing the mean concentrations statistically (Appendix 5) suggests that several elements change significantly when watering regime is varied. These include Cu, K, Ni, Pb, Zn and S. Some of the elements are highest in optimally watered plants, and lowest in waterlogged ones. These include Cu, Zn and S. and K have the highest concentrations in droughted plants and lowest in waterlogged ones. Pb concentrations are much higher in optimally watered plants and lowest in droughted ones.

The Experiment 5 dataset is probably the most significant of all in this experimental work because it assists the investigation of the field conditions under which crop marks appear with most clarity and regularity, that is when there is an SMD. In the droughted plants (Table 6.26) a more varied pattern of enhancement and depletion of plant concentrations were noticeable, similar to those in the optimally watered plants. Generally the shallow soil depths produced more plants with increased concentrations than with depleted ones, whilst medium soils supported a similar number of nutrient-enhanced and nutrient-depleted plants. Of the three elements with different concentrations associated with deep soils Fe and K

showed enhanced levels and Zn was relatively depleted, although its concentration varied little between plants grown in the different soil depths. This was the only watering regime that produced variations in Cu concentrations, with a relative depletion in plants grown in medium depth soils. This subset of the data suggests that soil moisture is an important factor, but as the optimally watered plants also showed variations in concentration, the conclusion to be drawn is that there must also be variations in depth of soil to allow a partitioning of nutrient concentrations to develop. It serves only to confirm that crop mark formation is not a result of one singular factor, as the examination of the literature concluded in Chapter 2.

Table 6.24: Relative Elemental Concentration Variations in Optimally Watered Plants

Element	Shallow Soil	Medium Soil	Deep Soil	Concentrations Same	Statistically Significant
Ca			High		
Cr		High	Low		
Cu		High			Yes
Fe	High		Low		
K		High			Yes
Mg	Low		High	Yes	
Mn	Low		High		
Zn	Low		High		Yes
Na		High			
S	High		Low	Yes	Yes

Table 6.25: Elemental Concentration Variations in Waterlogged Plants

Element	Shallow Soil	Medium Soil	Deep Soil	Concentrations Same	Statistically Significant
Ca		Low			
Cr		Low	High		
Cu				Yes	Yes
Fe		Low	High		
K		Low	High		Yes
Mg		Low			
Mn		Low	High		
Zn		High			Yes
Na		Low			
S		Low			Yes

Table 6.26: Elemental Concentration Variations in Droughted Plants

Element	Shallow Soil	Medium Soil	Deep Soil	Concentrations Same	Statistically Significant
Ca		High			
Cr	High	Low			
Cu	High	Low			Yes
Fe		Low	High		
K		Low	High		Yes
Mg		High			
Mn		High			
Zn	High		Low	Yes	Yes
Na		High			
S	High	Low			Yes

Discussion of Results of Experiment 5

Tables 6.24 to 6.26 indicate that elemental uptake does change with different depths of soil, and with watering regime. Plates 6.21 and 6.22 show that whereas crop appearance changes if watering regime is varied, for the individual watering regimes changing soil depths does not produce a significant change in plant growth or appearance. This suggests that although chemical differences do occur with depth within watering groups, these changes do not necessarily result in visual differences. To change plant uptake in a way that causes visible changes in growth the watering regime must vary either independently or in conjunction with soil depth.

Changes in chemical composition of the plants from experiment 5 are evident where changing soil depth is the only variable. This suggests that elemental uptake is altered according to the amount of topsoil present locally, but for some reason the elemental differences tend not to be expressed as significant growth differences *unless* soil moisture differences also exist.

Although the traditionally described crop marks over positive and negative buried features can be hypothetically ‘created’ from the plants produced during Experiment 5, they do not entirely fit the norm, particularly for buried extant features, which to achieve the desired crop effect must comprise waterlogged rather than droughted plants grown in shallow soils. There are several points to be made about this, and not least important is that all the often quoted reservations about this being a pot-based experiment that is emulating a field situation must be applied here. Leaving this to one side, and bearing in mind that generally the empirical and observed data do seem to correlate quite well, one suggested explanation

for this apparent dichotomy between expected and observed results is that the cause of negative crop marks can on occasions be misunderstood. It is possible that many negative crop marks may be caused by waterlogging rather than droughting, and this is not unfeasible given the fact that negative crop marks tend to appear over features that are capable of preventing adequate drainage locally thus depriving barley roots of an adequate oxygen supply, resulting in the taller, lighter coloured, less dense growth of the negative marks, as illustrated in this experimental work. This is discussed further below.

Most importantly this experiment has established that changes in soil depth alone are unlikely to be responsible for the formation of archaeological crop marks. The traditionally accepted explanation that water affects growth has been shown to be the case, and to be a major influence on the appearance of plants grown here, irrespective of soil depth. Differences in elemental compositions of the plants however do suggest that although water availability is the main influence, other factors, including depth are at play, and affect the ability and efficacy of plants to utilise the available nutrient pool. In this respect depth does have a role, as it is also indicated as a major influence of the clarity with which crop marks are revealed.

6.7 Case Study 3: Analysis of Soils Excavated During Trial Trenching

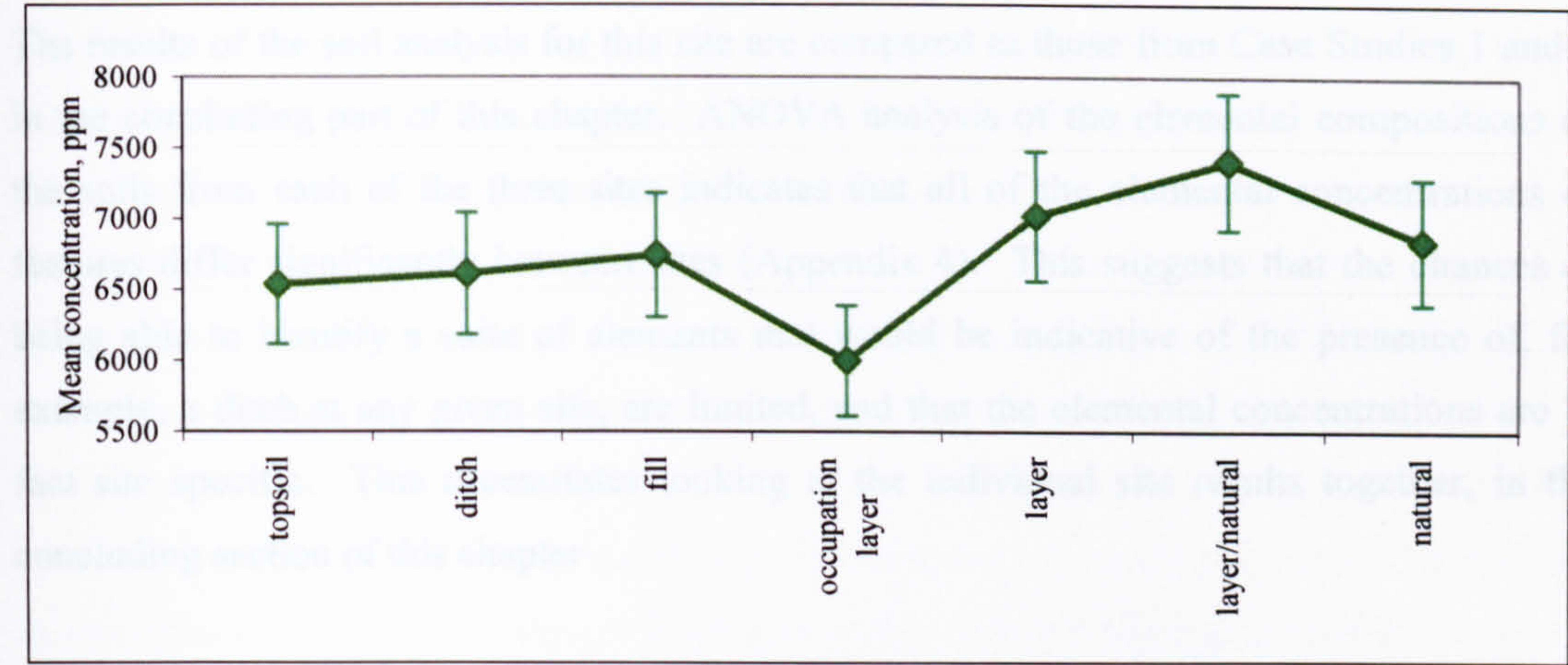
Examination of data from this final Case Study does not involve plant growth investigations. Case Study 3 provided soils, collected during excavation, that were analysed using ICP-MS, and the results of those analyses are presented here. This Case Study is effectively a test case for the experimental data. As was discussed in Chapter 5, Case Study 3 does not produce regular crop marks, is constantly kept under pasture and is seldom ploughed, and despite finding substantial archaeological remains that coincided with crop mark evidence for the presence of the circular enclosures, it did not produce coherent geophysical responses. Consequently the data generated during the analysis of soils will first be examined to see whether any elemental differences can be detected from the excavated contexts (see Appendix 6 for information on the excavation), before the results are compared with those from the experimental work. Because these analyses are of contexts, the same limitations apply as did for the excavated soils used in Experiment 3. However, this is considered to be a meaningful comparison with the soils from both Experiments 2 and 3, on the basis that assessment of the differences between the Experiment 3 augured and excavated

soils in the discussion of Experiment 3 analytical results revealed no statistically significant differences in the analyses of the excavated and augured soils there. From the analyses of soils from Case Study 3 it can be seen that a high number of elements are depleted in the ditch and other fills at the site (Table 6.27), and in the natural. Mg is the only element that fails to produce a significant pattern of concentrations in this dataset (Figure 6.40a), although it does show a gradual increase in concentration with depth, with the exception of the occupation layers which are significantly depleted. Of the elements that were enriched in the ditch fills Zn and S had the most markedly elevated concentrations, and Ca and P concentrations were also shown to be increased in the ditch samples (Figure 6.40b). Ca and S were also enriched in the occupation layers. Ca enrichment in the occupation layers is likely to be a consequence of the incorporation of large quantities of burnt bone in the floor of the hut circle (Appendix 2). Ca, together with P values tended to decrease with depth. Both the natural and the layer sampled from the site had higher Ti, and to a lesser extent K concentrations and this information will be taken into consideration during the final interpretation of the features excavated at the site (Hanson and Sharpe in prep).

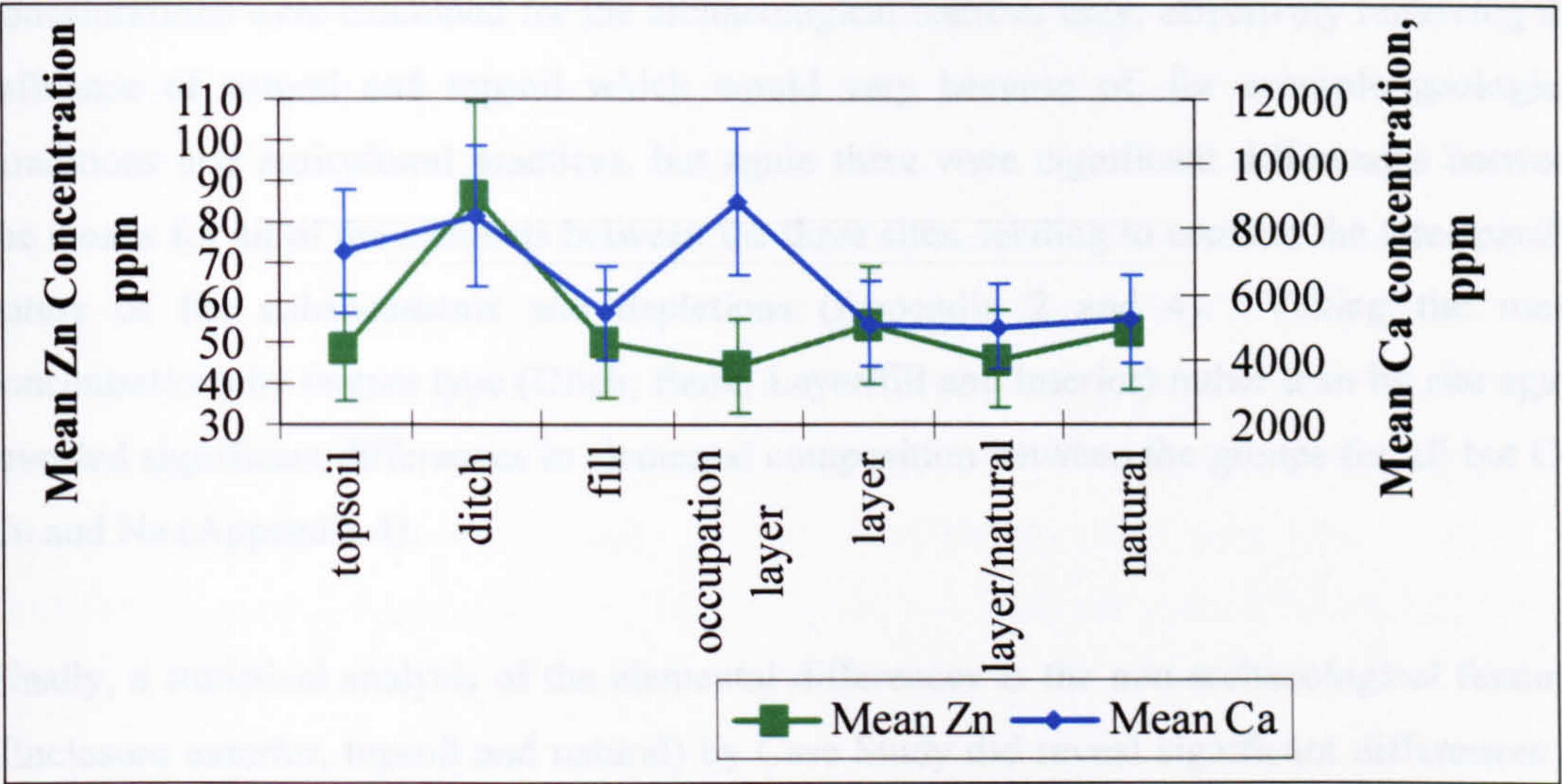
A statistical analysis of the data suggests that of all the elements, the differences between means of concentrations from the individual contexts are significant for P, Zn and S. For all three elements, concentrations are highest in the ditch samples, and for Zn in particular this feature type is the only one producing significant concentration changes. Each of the elements also have low concentrations in samples taken from a layer close to the natural, whose interpretation as anthropogenic was uncertain. However, the depleted nature of the medium suggests that it is indeed a distinct archaeological layer, having a different elemental composition from the natural.

Table 6.27: Summary of the Elemental Concentrations Measured for the Contexts at Case Study 3

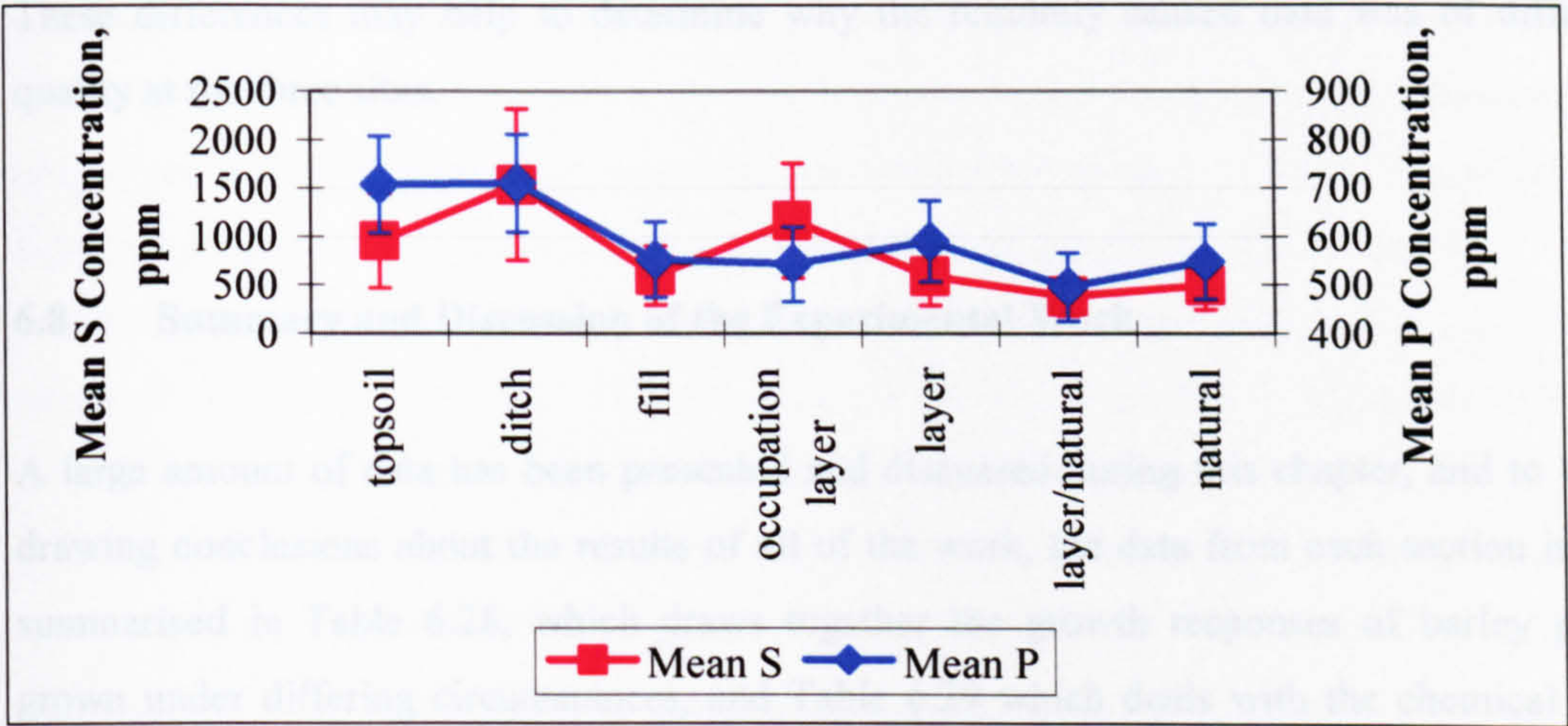
<i>Feature</i>	<i>Concentration Increased</i>	<i>Concentration Decreased</i>	<i>Statistically Significant</i>
Ditch	Zn, S, Ca, P	Al, Cd, Cr, Fe, Mn, Ni, Ti, Na, ~K	P, Zn, S
Other fill	None	Ca, Cd, Co, Cr, Cu, Fe, Mn, Ni, P, ~K	
Layer	K, ~Ti	P, Pb	
Natural	Ti, ~K	Al, Ca, Cd, Cr, Cu, P, S, ~Ni	
Topsoil	Cu, Mn, P, Pb	None	
No obvious pattern	Mg		



a)



b)



c)

Figure 6.40:
Graphs of average concentrations for contexts at Case Study 3: a) Mg; b) Zn and Ca and c) S and P.

The results of the soil analysis for this site are compared to those from Case Studies 1 and 2 in the concluding part of this chapter. ANOVA analysis of the elemental compositions of the soils from each of the three sites indicates that all of the elemental concentrations of features differ significantly between sites (Appendix 4). This suggests that the chances of being able to identify a suite of elements that would be indicative of the presence of, for example, a ditch at any given site, are limited, and that the elemental concentrations are in fact site specific. This necessitates looking at the individual site results together, in the concluding section of this chapter

In an attempt to identify any general differences at the three Case Studies, the elemental concentrations were examined for the archaeological features only, effectively removing the influence of natural and topsoil which would vary because of, for example geological conditions and agricultural practices, but again there were significant differences between the means for all of the elements between the three sites, tending to confirm the site-specific nature of the enhancements and depletions (Appendix 2 and 4). Taking the mean concentrations by feature type (Ditch; Bank; Layer/fill and Interior) rather than by site again revealed significant differences in elemental composition between the groups for all but Co, Cu and Na (Appendix 4).

Finally, a statistical analysis of the elemental differences in the non-archaeological features (Enclosure exterior, topsoil and natural) by Case Study did reveal significant differences in mean concentrations of Al, Ca, Cd, Cr, Mg, Mn, Ni, P, Pb, Ti, Zn and Na (Appendix 4). These differences may help to determine why the remotely sensed data was of differing quality at the three sites.

6.8 Summary and Discussion of the Experimental Work

A large amount of data has been presented and discussed during this chapter, and to begin drawing conclusions about the results of all of the work, the data from each section is first summarised in Table 6.28, which draws together the growth responses of barley plants grown under differing circumstances, and Table 6.29 which deals with the chemical data. Table 6.28 shows the least correlation between responses of plants grown in soils from the two Case studies, although for Case Study 1 soils, the table shows that there are certain growth responses that appear to be independent of watering regime, for example the

consistently low germination rates in topsoil under the three different moisture availabilities. No obvious patterns can be associated with the harvested weights of the plants from the individual sites either. Some generalisations can be made however, for example average heights for the plants tend to be increased in topsoils and ditch soils, with features associated with banks tending to produce shorter growth at Case Studies 1 and 2, except for in optimally watered soils at the former where ditch grown plants were the shortest.

In addition to the lack of conformity of growth characteristics at the two sites, it is difficult to make direct comparisons between the plants grown in archaeological soils in Experiments 2 and 3 and those grown in compost in Experiments 4 and 5, without stretching the bounds of the hypothetical too far by translating the watering and depth changes into equivalent archaeological 'features'. Taking the last two experiments separately for this reason it can be seen that tillering is affected by water stress, but that the effect tends to be buffered slightly when soil depths are increased, tending to confirm the existence of the reservoir effect discussed in Chapter 2 when considering the effects of SMD on growth and development. Soil depth can also be seen to affect plant heights, with deep soils producing taller growth and shallow soils giving rise to shorter plants. This is almost certainly related to maintenance of a shoot/root ratio characteristic for the individual plant species, in response to external factors such as volume of soil available for growth (Marschner 1995, 535-6).

Chemically there is more correlation between enhanced and depleted elements in the soils and plants analysed from all of the experimental work (Table 6.29). For the soils a number of elements were shown to produce no discernable or explicable patterns of concentration in any of the archaeological soils, and these are considered to have little or no input to the signals recorded during remote sensing. These elements are Cr, Al, Zn, Ni and Mg. Of the remaining elements the ditches in particular revealed that many were either depleted or enhanced at each of the sites. This revealed that Pb and P tend to be concentrated in the topsoil or external to the enclosures. With the possible exception of the enhancement at Case Study 3, which excavation suggests had at least one area where lead smelting had been carried out, the raised Pb levels are assumed to be associated with modern air pollution, although the levels could also have a soil chemical explanation as they quite often appear in association with P and S, the latter of which may also represent a modern pollution input. It is interesting that P levels should tend to be concentrated outside of the enclosures given its generally accepted ability to inform about on-site activity or location. It is likely that its

distribution as presented here is skewed because of the combining of topsoil and enclosure exteriors in this analysis, and as it is concentrated in excavated topsoil samples at Case Studies 1 and 3 this is the most likely explanation, rather than an off-site enhancement as the table suggests. Fe and K concentrations are also seen to be depressed in these samples, suggesting on-site enhancement. As this pattern does not extend to Case Study 3 this may point to why the geophysical anomalies were not clear at this site. This suggestion is given weight by the absence of any Fe enhancement in the features at Case Study 3, as opposed to that noted at the first two sites. At Case Study 2 the ditch and interior have higher Fe concentrations, while at Case study 1, where the magnetic anomalies are reversed, the ditches are depleted in Fe but the bank soils are enhanced. This suggests that Fe does play an important part in the production of remotely sensed signals at the sites. There is a tendency for Mn, Ti, K and Cu levels to vary in the same way as Fe.

Elemental variation was highest over the ditches at the 3 sites, and in some cases the same elements appear as both enhanced and depleted in Table 6.29. This is a consequence of pulling data from similar features at the 3 sites together, and helps to illustrate that despite hoping for a very clear cut conclusion to this thesis (“the answer to life, the universe and everything”) it is obvious that each individual site examined here has its own unique chemical fingerprint. However, in the hope of achieving the aims of this thesis, it is assumed that these elements, for example S and Pb from the augured ditch soils, can not be ‘indicator’ elements. Discarding these leaves the smaller numbers of elements that have potential to shed light on remotely sensed data in Table 6.30.

For Case study 1, the chemical differences between the ditch soils and the reversed ditch anomaly lay with those that are enhanced rather than depleted, with the reversed anomaly also having raised levels of Ca, Na and Cu. Na is also indicative of the interiors of the enclosures at case Studies 1 and 2.

Where the geophysical anomalies indicate changes in properties for ditches, such as at Case Study 2, the experimental results show that growth characteristics also change, with for example the reverse anomaly at the outer ditch there exhibiting a shorter growth trend than that measured over the portion of the ditch that produced the main ditch anomaly (in this case low resistance, although the local background is lower still, and negative magnetic readings). This suggests that the postulated change in subsurface characteristics detected geophysically reflects an actual change in the physical properties of the soil that affects crop

growth. The MS values associated with the changing ditch anomalies suggests that the iron minerals present at the site are largely diamagnetic in nature, with the change to positive values over the bank and reversed bank anomaly suggests that here a paramagnetic component dominates. Linking this to geophysical responses, the results again suggest elemental differences in the soils comprising these different features. As discussed earlier however, the correlation of LF with HF values and therefore the low FD of these samples suggests that the variations are likely to be largely natural, suggesting a pedogenic rather than anthropogenic origin for the differences.

Al, Mn, Ti and Na concentrations were found to be reduced in any plants that underwent waterlogging or droughting at any stage during their growth, whereas Zn concentrations were decreased in waterlogged plants, and particularly those that grew in originally wet conditions, whilst the concentrations increased where there was droughting. Therefore, uptake of these elements can be said to be linked to water availability. This suggests, and is discussed during the analysis of Experiment 5 results, that watering regime has a larger impact on the development of growth and appearance of crop plants than changes in soil depth, although the experimental results suggest that shallower soil depths, in combination with differential water supply, encourage the development of archaeological crop marks even if the features do not comprise cut features or extant remains that change the soil depths significantly.

Table 6.29b shows the patterns of enhancement in the plants grown in archaeological soils. The vast majority of the plants displayed no context-related variations in nutrient elements. The only exceptions to this were the ditch soils which produced plants with elevated Fe and depleted levels of K. At Case Study 1 the Fe levels were only elevated in waterlogged soils, and the depressed K levels were not noted in plants that had been droughted, whereas these patterns emerged in the plants grown in ditch soils from case study 2 that had all been optimally watered.

Table 6.29c summarises the experimental results of the plants grown in compost (Experiments 4 and 5). The results of these analyses reveal much more variety in the elements depleted and enhanced than those plants grown in archaeological soils. This is assumed to be because the composts are designed to provide full nutritional requirements of pot-grown plants, unlike isolated soil samples which represent only a part of the bulk soil

normally available for plant nutrition, particularly where samples are taken from isolated excavated samples.

Generally there were a number of elements that became enriched or depleted in the barley depending on the watering regime that it was subjected to. Attempting to group these elements in a simplistic way was made difficult because the significant elements also depended on the depth of soil that the plants were grown in. In Table 6.32 the Experiment 4 plants and the shallow soil depths from Experiment 5 were grouped together, followed by the medium and deep soil-grown plants of Experiment 5.

In addition it is difficult to relate the differences directly to the archaeological results as discussed. However the summary can be used to help assess which elements are likely to vary with moisture availability and, as the preceding discussions of the experimental results have shown, the growth differences investigated there can be linked to elemental differences, which in turn can be assessed in the light of the differences in archaeological soils and plants produced in them, which thus provide a link back to the geophysical responses, and return us to the questions posed in Chapter 1. In the next chapter, this work is drawn to a conclusion using the results of the remotely sensed data from Chapter 5 together with those from the experimental work of this chapter to attempt to answer those questions.

As with the variations in mean soil concentrations, statistical analysis of the analytical data from the plant materials showed that all elements varied significantly between experimental groups, again suggesting that elemental variations are site specific (Appendix 5).

Table 6.28: Growth Differences Recorded in the Experimental Work

Experiment	Variable	Germination		Average Nos of Tillers		Average Heights at Harvest		Average No of Leaves		Harvest Weights	
		High	Low	High	Low	High	Low	High	Low	High	Low
2	Optimal	Outer Ditch reverse anomaly; Interior	Outer ditch; Inner ditch branch; Exterior	na	na	Outer ditch	Outer Ditch reverse anomaly	Outer ditch	Inner ditch	Outer ditch	Inner ditch
3	Optimal	Bank	Topsoil	Ditch	bank	Topsoil	Ditch	Topsoil; ditch	Bank	Topsoil	Bank
3	Waterlogged	Ditch	Topsoil	Topsoil; Ditch	Bank	Topsoil	Bank	Topsoil	Bank	Topsoil	Bank
3	Droughted	Bank	Topsoil	Bank	Natural; ditch	Ditch	Bank	Ditch	Bank	Topsoil	Bank
4*	Harvest 1	No data	No data	Optimum	Dry & wet	Optimum	dry	Optimum	Dry	Optimum	Dry
5	Optimal	Medium depth	Shallow depth	All	na	Deep soil	Shallow depth	na	na	Deep soil	Shallow depth
5	Waterlogged	Shallow depth	Medium depth	na	All	Deep soil	Shallow depth	na	na	Medium depth	Shallow depth
5	Droughted	Medium depth	Shallow depth; Deep soil	Deep soil	Shallow and medium depths	Deep soil	Shallow depth	na	na	Deep soil	Shallow depth

Table 6.29: Chemical Differences Recorded During the Experimental Work: a) soils and b) plants

a) Soils

Expt No	No Obvious Pattern	General On-site		Exterior/Topsoil		Ditches/Fills		Banks/Reverse Ditch Anomalies		Interior		Natural	
		High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
2	Al, Cr, Ca	Fe, Mn, Cu, Cd, Mg, Ni	none	Pb	Fe Mn Cd Ni K	Na, Cd, Co, Cu, Fe, Mn, K, Mg, Pb, Ti, Na	P, S	None	Na	Cd, Cu, Fe, K, Mn, Ni, Co, P	No data	No data	No data
3 Excavated	Co Zn Ni Cr	No data	No data	Ca P Pb	K Mg Na Al Fe	P	Al Fe K Cu Cd P Ti Mn Pb	No data	No data	No data	No data	K Mg Ti	Ca P S
3 Augured	Cd Mg Ni Al Zn	None	none	Al P	Fe	Co Cr Fe K Mn Ti P Pb S	P S Cu Pb	Reverse anomaly: Ca Co Cr Cu Fe K Mn Ti Na; Bank: Co Fe K Mn Ti	Na	P S	No data	No data	No data
Case Study 3	Mg	No data	No data	Cu Mn P Pb	None	Zn S Ca P	Al Cd Cr Fe Mn Ni Ti Na K Ca Co Cu P	No data	No data	No data	No data	Ti K	Al Ca Cd Cr Cu P S Ni
Common elements	Mg Cr Zn Ni	None	none	Pb P	Fe K	Co P	P Al Cu	Co Fe K Mn Ti	Na	P	No data	Ti K	Ca P S

b) Plants from Archaeological Soils

Expt No	Watering Regime	Unreliable	No Obvious Pattern	Exterior/Topsoil		Ditches/Fills		Inter-ditch		Interior	
				High	Low	High	Low	High	Low	High	Low
2	Optimal	Mo Co P Ti Ni Cd	Cr	Mn	Mg Pb S Zn	Al Ca Cu Fe Mg Na	Mn, K	Zn	Al Fe Mn Na	Mn Na S	none
3	Optimal		Ca				K S				
3	Wet					Fe	K S				
3	Dry					K	S				
Common elements						Fe	K				

c) Plants from Compost

Experiment	Watering Regime	High Concentration	Low Concentration	Unreliable	No Obvious Pattern
4*	Optimal	Mn		Mo Cd Co Ti Ni P	Ca Mg
4*	Waterlogged	Ca Fe Mn	Cr Cu K Zn S		
4*	Droughted	Cu K Pb Zn S	Cr		
4	Moisture stress	Pb	Al Cr Mn Na		
5	Optimal	Shallow: Fe; Medium: Cu K Na; Deep: Ca Mn Zn	Shallow: Mn Zn; Deep: Fe Mo	Mg S	Cu
5	Waterlogged	Medium: Zn; Deep: Cr Fe K Mn	Medium: Ca Cr Fe K Mg Mn Na S		
5	Droughted	Shallow: Cr Cu Zn S; Medium: Ca Mg Mn Na; Deep: Fe K	Medium: Cr Cu Fe K S		
Common elements		Mn Fe Cu K Zn	Cr S Mn Fe K		

*Harvest 1 results (before water regime changes)

Table 6.30: Significant Elemental Variations

	Not Relevant for Remotely Sensed Characteristics	Topsoil/Exterior Elevated	Topsoil/Exterior Depleted	Ditch/Fill Elevated	Ditch/Fill Depleted	Bank/Ditch Reverse Anomaly Elevated	Interior Elevated	Interior Eepleted	Natural High	Natural Low
Soil	Mg Al Cr Zn Ni	Pb P	Fe K	Co	Al Cu Cd	Co Fe K Mn Ti	P	Na	Ti K	Ca P S
plants				Fe	K					

Table 6.31 Significant Elemental Variations in Compost-grown plants

Plant Growth Conditions	High Concentration	Low Concentration
Optimum shallow-grown	Fe	Mo Zn
Wet shallow-grown	Mn Fe Mo	Cr Cu K Zn S Ni
Dry shallow-grown	Cu K Ni Pb Zn S Cr	Cr Mo
Optimum medium	Cu K Na	
Optimum deep	Ca Mn Zn	Fe Mo
Wet medium	Zn	Ca Cr Fe Mg Mn Mo Na S
Wet Deep	Cr Fe K Mn Mo	
Dry medium	Ca Mg Mn Mo Na	Cr Cu Fe K S
Dry Deep	Fe K	

Chapter 7: Discussion and Conclusions

7.1 Introduction

This chapter draws the work for this thesis together, examining the results of the various surveys and experiments, before bringing it to a close. The answers to the five questions posed in Chapter 1 are the basis for its content. The means of answering the questions is provided by the analysis of aerial photographic information, collection of geophysical data and excavation and soil samples at the three Case Studies (Chapters 3 and 5), together with the programme of experimental work (Chapter 6). The experiments focussed on the qualitative examination of the crop responses to a series of cultural variations chosen because they were suspected, based upon the literature review in Chapter 2, of being responsible for crop mark development. The glasshouse-based work was followed by elemental analysis of certain archaeological soils gathered from the Case Studies, and plant groups grown during the glasshouse work. The aim of the analytical work was to attempt to identify changes in concentrations of elements due to either changes inherent in the different archaeological contexts, or to responses to altered cultural conditions. The objective of this work was to seek those elements whose changing concentrations might bring about changes in crop growth or geophysical responses in the locality of the enhancement or depletion, and preferably to find elements that would affect all three remotely sensed datasets where they correlate in the Case Studies. The additional benefit of using plants grown in the glasshouse environment was that any elemental differences discovered could be linked to the appearance of the individual plants, and could also be associated with the geophysical responses by linking sampling positions to the data gathered within the survey grids at the three sites. Sections 7.2 to 7.6 below individually address each of the questions posed originally, with final discussion and conclusions presented in section 7.7.

7.2 Why Do Crop Marks Form?

Chapter 2 discussed the current thoughts on the development of crop mark sites extensively. In this section the question is considered in the light of the research undertaken for this thesis. The experimental work presented in Chapter 6 shows that differential growth develops in plants that

are grown in soils taken from archaeological contexts and the soils augured from above such features at unexcavated sites. This differential growth was established in soils from Case Studies 1 and 2 in the absence of differential water supply (Experiment 2 and optimally watered plants in Experiment 3). This shows that it is not necessary for varying SMDs to be established within archaeological soils before differential growth develops over individual features. However, when variable watering regimes were applied to plants grown in excavated contexts from Case study 1 (Experiment 3) the differential growth recorded in the optimally watered plants was enhanced. This suggests that soil water availability does also influence the development of differential growth in barley, but that there are underlying causes for this which are enhanced when soil moisture content varies.

In an attempt to quantify the importance of water availability for establishment and continued development of differential growth this was the only variable cultural condition applied to those plants grown in Experiment 4. Again this experiment proved the commonly held consensus, that soil water differences do produce differential growth. However, this and the remaining experiment (5) highlighted an important feature of this moisture-induced differential growth, which was that droughted plants tended to be stunted, as predicted, but contrary to the expected lighter green growth they consistently produced dark green foliage, usually darker than that of the optimally watered plants, which would constitute positive crop marks in the field. Waterlogged plants too tended to be amongst the tallest of those grown during the experimental work, and were noticeably lighter in colour and possessed few tillers, giving them a stiff, sparse upright appearance such as that which would be expected from the plants comprising a negative crop mark.

Under field conditions it is generally accepted that positive crop growth develops over cut features that hold higher moisture reserves in the soils filling them (Chapter 2), and that positive growth comprises plants that are darker green and have taller stems and larger leaf areas (Jones and Evans 1975, 2). Negative growth develops due to droughting of plants that have germinated over features that increase compaction or reduce topsoil depth, the classic example being the buried remains of buildings. This situation results in shortened, lighter green plants with smaller leaf areas and less dense growth. There are occasional suggestions that negative growth responses also develop under conditions of waterlogging but this tends to be identified and mentioned more rarely than the droughting situation. They are mentioned in connection with the

presence of impermeable layers or pans that are present within 60 cm of the ground surface, tend to develop in shallow soils, and are thought to be the result of restricted root growth due to excess water (Jones and Evans 1975, 8-9).

Because crop marks have been observed to develop most extensively when an SMD exists, the assumption is that positive growth appears above wetter ground, and negative growth in drier ground than that surrounding it. However, on the basis of the experimental work this would produce negative crop marks that were darker and similarly or more dense than the 'positive' growth, and positive crop marks that were either of a similar or lighter hue depending on the level of soil moisture contained in the cut features. If the features retained so much more water than the surroundings as to move towards waterlogging, the 'positive' growth developing would actually appear as negative crop marks. This lack of correlation between experimental results and the field situation suggests, and Experiments 2 and 3 tend to confirm, that changing soil moisture alone can not be responsible for crop mark formation.

At Case Study 1 the interior has a patchy appearance on aerial photographs, and as discussed in Chapter 5 (Plate 5.2), some of these patches support positive growth but correspond with waterlogged areas. Additionally the bifurcated section of the southern outer ditch terminal, which appears in magnetic and aerial information to represent a banked feature but in fact exists as a topographically depressed area of standing water, do not correspond with the standard responses expected. Only the resistivity data gives the response expected for a waterlogged cut feature. While the cause of the geophysical responses to this and the remaining features at Case study 1 are discussed below, the crop responses, particularly at the terminal, tend to correlate with the experimental results. A second example of this correlation arose in the aerial photographic information from Case study 2, where the presence of a drain was marked by a negative crop mark, which suggests that the soil in the vicinity of the drain is likely to have resulted in increased soil moisture, producing growth that would be traditionally interpreted as a negative crop mark developed in response to a soil moisture deficit, but producing growth similar to that of the waterlogged plants in Experiment 4. This suggests that a more careful interpretation of reconnaissance results is required if the best interpretation of the site is to be achieved. Although the traditionally described crop marks over positive and negative buried features can be hypothetically 'created' from the plants produced during Experiment 5, they do not entirely fit the norm, particularly for buried extant features, which to achieve the desired

crop effect must comprise waterlogged rather than droughted plants grown in shallow soils. One suggested explanation for this apparent dichotomy between expected and observed results is that the cause of negative crop marks can on occasions be misunderstood, as discussed in Experiment 5. It is possible for example that many negative crop marks may be caused by waterlogging rather than droughting, which has implications for site preservation as well as the interpretation of the underlying features.

Returning to Experiment 4, the watering regimes were altered from the original treatments once tillering had commenced, with the altered watering regimes applied to the remaining plants after the first harvest. Although the growth characteristics of the plants subjected to this altered watering regime were changed by it, in most cases the growth patterns associated with the original watering regime had become established and did not alter sufficiently to be unidentifiable at the following two harvests. This is contrary to the field observations noted in Chapter 2 with regard to the removal of differential growth following prolonged rainy spells during summer months. It does, however, confirm the observations made in Scotland regarding the timing of wet weather throughout the year. It has been noted (and discussed in Chapter 2) that below average rainfall in May and June will tend to produce an above average record of visible crop marks, assuming that this period extends into July and August (M. Brown pers comm.). It does suggest that the growth patterns of field-grown crops are established early on, with tillering in spring barley probably beginning to start around May to June in Scottish crops. The lessening of differential growth described mainly for English reconnaissance is likely to be a consequence of factors working in association with soil moisture changes, such as timing of rainfall and nutrient supply, which was a constant factor in the glasshouse experiments, but is a dynamic system in the soil environment.

Jones and Evans (1975, 2) suggest that the effects of water and nutrient availability are most important when considering the reasons for differential growth because successful plant growth depends on the satisfaction of metabolic requirements. Reduced growth, producing negative crop marks, develops due to inhibition of nutrient uptake by the plant roots, which in turn leads to reduced respiration and photosynthesis (Jones and Evans 1975, 9). This has proved to be the case when these factors were examined during the experimental work. The results, together with the review of the literature undertaken in Chapter 2 suggests that soil moisture does play a substantial part in the development of crop marks, but that elemental variations play a similarly

important factor. Although uptake of nutrient elements depends critically on the soil moisture status, not only for providing a mechanism for uptake at the plant root-soil interface under optimal conditions, but also because under conditions of moisture stress soil chemical properties change due to altered pH and redox potentials, which change the chemical species of elements important for plant metabolism, and in some cases the elements then become unavailable or unusable to the plants, the experimental work suggests that there is more to the elemental availability than this. Analytical examination of the soils from all three Case Studies indicates that elemental variations exist within the different archaeological contexts, and for certain elements the variations between features are statistically significant. In addition, because the differences measured in the soils and those measured in the plant samples grown in them do not correlate entirely, particularly when differential soil moisture is added into the equation, it suggests that the differential growth in archaeological features is partly a response to the altered elemental concentrations, the 'archaeological component' and partly a soil chemical/pedological response which determines the availability of those altered elemental concentrations to plants, the 'soil cultural component'.

Finally, in Experiment 5 the effects of changes in soil depth were considered. This has again been cited as a factor in crop mark development as discussed in Chapter 2. The experimental work showed that watering regime has a larger impact on the development of growth and the appearance of crop plants than changes in soil depth, but that increasing soil depth tends to mask the effects of differential water supply. Translated to the field it suggests, and field observations (Jones and Evans 1975, 8-9) confirm, that as soil depth increases the chances of crop marks developing decreases. If subsurface soil volumes change due to the presence of cut features, Experiment 5 shows that there are negligible observable growth differences in plants even under standardised watering regimes. The joint effects of shallow soils and altered watering regimes, particularly if the features themselves contain contexts whose moisture holding capacities differ from the natural soil profile, is highly likely to result in a dramatic increase in the ability of the site to produce crop marks, even if the features do not have significant depths or extant remains thus changing the soil depths little. This could help to explain the phenomenon of ghost crop marks discussed in Chapter 2.

From the results of the experimental work in conjunction with field observations, it would appear that at the three Case Studies at least, crop mark formation is a combination of an

'archaeological component' and a 'natural/ soil cultural component', and development of differential crop growth is dependent upon soil moisture availability as predicted, but also upon elemental differences within the archaeological features, together with soil-environmental factors that may or may not be inherent to the archaeological remains. These factors control the availability for uptake by the crop plants of the nutrient elements present. This in turn helps to explain the geophysical responses and their close correlation at two of the three Case Studies.

7.3 Why In Two Of The Three Case Studies Do The Crop Mark Responses Coincide So Closely With The Geophysical Responses?

The experimental results discussed in Chapter 6 do not apply only to the question of crop mark development. The examination of the reasons for the differential crop growth necessarily demands a consideration of the soil properties at a site producing the crop marks, and this is where the properties responsible for anomalous geophysical signals also lie. Beginning with the simplest answer, the resistivity data responds to the changes in soil moisture associated with the cut features. However, even with the moisture differences removed, for example when the conductivity measurements were made for the Case Study 2 soils, the conductivities of the individual samples varied in such a way that the mean figures for the individual features were noticeably different. These bench measurements correlated well with the resistivity data collected over the site (see Chapters 5 and 6), which suggests that, as with crop mark formation, resistivity results are not entirely soil moisture-dependent. This has been stated throughout this thesis with regard to magnetic survey, and indeed was the initial impetus for the research. The answer then must lie with the soil chemistry.

Soil depth was shown to be of little significance to the production of crop marks, and it is suggested that this is also the case for geophysical results. Primarily, this variable is dismissed as a cause of resistance changes partly because the bench measurement of conductivity effectively removed not only the effects of soil moisture variations, but also of depth responses, and still produced results that correlated with the field situation. Additionally, the FM36 and RM15 tend to measure to average, fairly constant depths of *c.* 1.0 m and 0.5m respectively, so although there will be some input from the bulk soil above this depth, particularly for the magnetic data, there is unlikely to be an input from much deeper than it. This means that during

field measurement of geophysical properties the instruments effectively filter out depth differences to a large extent. This should not apply to shallower features that lie within the depths of detection however, and the fact that there were deep ditches at Case study 3 did not enhance the ability to detect them geophysically. This suggests that the fill of the feature is far more important than the depth of it, and adds impetus to the suggestion that the geophysical instruments must be responding to a factor other than moisture availability or depth changes. By the same token, magnetic susceptibility measurements for the features at Case Study 1, also independent of depth, showed large variation in measurements for both soils and plants. It is interesting to note that the susceptibilities of the plant samples changed depending on which watering regime they had been subjected to. As susceptibility depends to a large extent on the form that the iron minerals take in a sample, this suggests that water availability affects the redox potential of the available iron. This is important for the remotely sensed data and is discussed further below.

Soil chemical changes are the remaining mechanism indicated as having a role in the formation of crop marks, and they are almost certainly the reason that the geophysical anomalies reflect almost exactly the crop growth responses at Case Studies 1 and 2. The remaining questions are which chemical concentrations are responsible for the correlations, and what is causing them to change? Theoretically this should be an easy question to answer, especially because there are elemental analyses of the soils from Case Study 3, where remote sensing, and particularly geophysical prospection, was less successful. All that needs to be done is to find out what elemental differences there are in, for example the ditches, at the three Case Studies, and anything that appears as altered in Case studies 1 and 2 but not in Case study 3, or vice versa, is likely to be the element or suite of elements responsible for production of recordable geophysical anomalies and to a lesser extent, crop mark development. Unfortunately, as the conclusions to Chapter 6 proved, the situation is not that straightforward. For example, at Case Study 1 enhanced elemental levels of K, P, Pb and S were measured in soils taken from the ditches, while at Case Study 2 Mn and Al levels increased over the ditches there, while at Case Study 3 they were enriched in P, Zn and S. The data from the ditches suggests that P and S may be responsible for the absence or reversal of geophysical anomalies, such as those recorded at Case studies 1 and 3.

The hypothesis presented is that there are chemical differences in the archaeological features that result in enhanced and/or depleted levels of substances that are plant nutrients, and this accounts for the differential plant growth. These differences in elemental concentrations are also manifest at the atomic level, giving differences in ionic concentrations, which result in differing abilities of movement of electrical charge, and in turn, changes in electro-magnetic properties of the subsurface. Although elemental differences were detected at each of the sites, the indication is that the differences are site-specific.

The experimental data has shown that elemental differences exist in the soil and plant analyses, and that in at least two cases (Experiment 2 and optimally watered plants in Experiment 3) this is the only cultural variable that can explain the differential growth. To be able to say something about the concentrations of electrons associated with these changes, Eh measurements (redox potential) would have to have been made for the samples. This was not undertaken, and is something to be considered for future work. However, measured concentrations, together with conductivity, MS and pH data where available, allow us in combination to say something about this change in oxidation state of the elements and the soil environment generally, in a less direct way. This measurement of elemental differences in the soils and plants is considered next relative to the changing responses of the prospection techniques.

7.4 Are There Geochemical Differences That Can Account for the Responses that Are Common to All the Remote Sensing Techniques Applied at These and Other Sites?

The factors that link crop mark formation and geophysical responses are considered here. Because differential water supply has been largely discounted as the sole cause of all of these responses, and changes in depth have also been ruled out, effectively at the same time removing the idea of changing volumes of soils, water and nutrients having a reservoir effect for crop and geophysical responses as a factor, there remains the soil chemical environment. Within this environment, the behaviour and movement of solutes in soil solution in general and at an atomic/molecular level are considered to be the fundamental link between the development of differential crop growth and the geophysical responses. There are two avenues to be explored in this respect; the first is the general enhancement of elements in the archaeological soils, which Experiments 2 and 3 have shown to exist. The second is the alteration of the chemical species

and of the oxidative environment either due to water levels, or to properties inherent to the individual archaeological contexts, that result in changing availability of elements for uptake by plants.

Taking the elemental concentrations first, each of the experiments presented in Chapter 6 had tables summarising the elemental concentrations for the plants and soils, and in the conclusions the general trends were indicated in a final summary table. First, it is clear from the number of elements highlighted as significant in these tables that there is not going to be a clear-cut answer to these questions. However, analysing the mean concentrations of individual elements statistically reduced the number of elements that were significantly different for individual contexts, while the mean data allowed something to be said about the soil environment generally at the individual sites.

P tends to accumulate in the organic rich topsoil and its concentration declines gradually with depth. Table 6.25 indicates that this is the case based on the analyses, with P concentrations elevated in topsoils, enclosure exteriors and interiors. Although Scollar *et al* indicate that phosphorus compounds have not been proven experimentally to differ within archaeological features compared to the surrounding undisturbed soils (1990, 56), at Case Studies 1 and 3 it was found to be elevated in the ditch soils, whilst at Case Study 2 ditch concentrations were lowered. Phosphate forms insoluble salts with Fe, Al and Ca. Hydroxyl-Al polymers that form on clay surfaces in the pH range 4.5-7 can adsorb phosphate by ligand exchange. The compounds are most stable between pH 5-6.5. In addition to this Al can replace anything up to 30% of Fe in some Fe oxides, such as goethite (White 1987, 25). Table 6.25 shows Al as being one of the elements that tends to be depleted in ditch and other archaeological fills, for example in the ditch fills of excavated soils of Case Studies 1 and 3. At Case study 2 however Al, together with Mn, is enhanced in the ditch soils. This is discussed further below.

Above pH 6.5 phosphate forms insoluble salts with Ca, for example octacalcium phosphate ($\text{Ca}_8\text{H}(\text{PO}_4)_6 \cdot 5\text{H}_2\text{O}$) which reverts to more stable hydroxyapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) (White 1987, 108). There are a high number of occurrences of Ca in combination with P in the soil analyses, which are summarised in Table 7.1, which together with the occurrences of Fe and Al are used to make assumptions about the pH of the soil environment. This suggests that Case Study 2, the site that responded 'normally' on the whole geophysically, has a more alkaline soil

environment than the remaining two sites. The known situation on the ground at Case Studies 1 and 3 would tend to confirm this, with both having a higher tendency towards waterlogging, which is known to cause more acidic subsurface conditions due to depleted oxygen supplies. The exception to this generally higher pH is likely to occur internally at Case Study 2, where Fe and P were enhanced. Figure 6.5b does reveal this to be the case, with only the reversed ditch anomaly and the inner ditch branch anomaly (see Chapters 5 and 6) having lower pH values. By contrast the features at Case study 1 tend to be of a more acidic nature on the basis of their phosphate chemistry, with discrepancies arising between the topsoil/exterior samples in the excavated and augured soils. At Case study 3 decreased levels of Fe and Al in the ditch soils tend to confirm the alkaline nature suggested by the enhanced Ca and P, while decreased Ca, Fe and P in fills taken from other contexts at the site suggest that they are more acidic. The similar mix of depleted concentrations in the natural is assumed to be a reflection of the highly gleyed soils at this site resulting in sampling of the natural at changing redox fronts.

The interesting and significant point to note from this examination is that the pH environment suggested at the three sites is a reflection of the geophysical responses. Case Study 2 tends to have a generally less acidic environment, and the field situation indicates that it is a more freely draining site. This site produces the most ‘orthodox’ geophysical responses, as discussed previously. Case Study 1 however, with the exception of the excavated topsoil samples and the natural, revealed combinations of these elements that would indicate a more acidic soil environment. At this site although the resistivity anomalies tend to be ‘normal’ and of a similar nature to those detected at Case study 2, the magnetic anomalies are all reversed. As iron chemistry is particularly affected by pH this must have some bearing on the magnetic responses recorded. Case study 3 has a similar soil environment to Case study 1, although as described above, the poor drainage at the site is more extreme in the former and is thought to be responsible for the mixed combinations of elements combining with the soil phosphates, representing a changing redox environment which adversely affects the remotely sensed data.

As Table 6.12 (Chapter 6) indicates, the iron chemistry, in this case mainly oxides of iron, along with for example Cu and Ti, is responsible for the magnetic behaviour of a material. This suggests that one of the first causes of elemental soil changes that can be linked both to differential crop growth via the experimental work and remotely sensed data presented here is based around these changes in iron and phosphorus chemistry that are associated with pH and

redox changes due to changes in drainage properties at the case Studies. As Ca and P have been implicated in root elongation and penetration down a soil profile where they are present (Chapter 2), it follows that where these elements are enhanced the likelihood of a positive crop mark developing is increased. Scollar *et al* (1990) suggest that remnants of stone and mortar walling could provide additional nutrients, such as Ca. This tends to be confirmed in work by Wilson *et al* (in prep), but one would expect positive crop marks in the areas around building remains as a result of this proposed increased root development aided by Ca, whilst the anticipated response to such remains would be a negative crop mark, with aerial photographs of crop mark sites over walling usually betraying evidence of insufficiency rather than additional support for growth. As discussed in Chapter 2, this observed result may be due to a lime-induced chlorosis, another factor that changes the availability of Fe to plants, as this example of soil chemical factors indicates, or alternatively it may be due to the mechanisms that cause negative crop marks to occur in response to droughting as discussed in Chapter 6 and above.

Table 7.1, summarising results taken from Chapter 6, indicates that this combination of Ca and P arises in the topsoil and outwith the enclosure at Case Study 1, and in the ditches and certain of the fills of other cut features at Case Study 3. At the latter, positive growth is present, whilst the undisturbed ground outside the enclosure at Case Study 1 produces what would be described as ‘average’ rather than positive growth.

Table 7.1: The Occurrence of Fe, Al and Ca With P In The Soil Analyses

Case Study	No Obvious Pattern	Exterior/ Topsoil High	Ditches/ Fills High	Ditches/ Fills Low	Interior High	Natural Low
1 Excavated		Ca P. alkaline	P	Al Fe. acid		Ca P. alkaline
1 Augured		Al P. acid	Fe P. acid		P	
2	Al Ca. alkaline			P	Fe P. acid	
3		P	Ca P. alkaline	Ca Al Fe P. Both		Al Ca P. Both

In the soil S display similar naturally-occurring distributions to P, although phosphorus content declines more rapidly with depth as the phosphate ion is quite immobile in soil (White 1987, 154). At Case Studies 1 and 3 S is depleted in the natural. On this basis S concentrations, without the need for discriminant or other statistical analysis, can be largely attributed to natural soil processes rather than anthropogenic ones. Pb, which is enhanced in the topsoils of all three sites, but only varies significantly between features at Case study 1, is also explicable in this simple way, due to modern particulate deposition of this element in airborne pollution associated with vehicle exhaust emissions. However, Pb is likely to be archaeologically significant at Case Study 3 given that Pb ore was discovered at the site in connection with probable metal working evidence. Co and Pb are often found in association with Mn oxides in soils (White 1987, 25) and this association is noticeable in the enhanced bank and reversed ditch anomaly soils at Case Study 3, although Mn only appears to be statistically significantly different in features at Case Study 2.

As well as Fe, the elements O, Ti and Cu are also implicated in the magnetic behaviour of soils and other materials. Oxygen levels in soils change with changing aeration, which is dependent upon soil structure, specifically the size and size-range of the soil particles, and of course on drainage. As discussed previously not only does drainage affect redox potential, but it also varies considerably at each of the three Case Studies, providing yet another example of why the magnetic surveys at the three sites ranged from very successful, very successful but with reversed anomalies detected, to only producing responses where strong thermoremanent signals were present. Although there were no significant variations in Ti concentrations at any of the sites, Cu concentrations showed significant variation between features at Case Study 2. This suggests different magnetic properties exist in these contexts and again points towards an explanation for the production of 'normal' anomalies over the features at Case Study 2, compared to the responses at Case Studies 1 and 3. It is likely that there is a ferrimagnetic and a diamagnetic input to the magnetic properties, whereas the elements responsible for this magnetic behaviour are all depleted in the ditch samples of the latter two sites. There is a general diamagnetic enhancement over the area of the site, as indicated by the Fe and Cu enhancement generally, which is not observed at Case studies 1 and 3. Additionally in the topsoils of Case Studies 1 and 2 Fe itself is depleted, whereas at Case Study 3 there is enhancement of Cu in the topsoil, which is likely to increase MS and have the effect of blanketing any more subtle underlying features, thus contributing to the lack of contrast magnetically at the site, an effect

noted at sites in Perthshire, although at these sites only the MS values were known for the contexts and not the elemental compositions (Sharpe 1996; 1998). As Table 7.2 shows the subsoils at Case studies 1 and 3 have similarly enhanced elemental levels, suggesting that these elements are responsible for the changed magnetic anomalies relative to the typical responses from Case Study 2.

As with this data, several recent studies have revealed definite variations in elemental concentrations across archaeological sites (Entwistle *et al* 1998; 2000; in prep; Wilson *et al* in prep). Although there have been shown to be variations in pH between features at the work undertaken for this thesis, Entwistle *et al* state that at the sites involved in their investigations “The relatively narrow range of pH values observed across the fields however, implies that the elemental variations observed within the soils may be largely due to other factors, over and above variations in pH.” Archaeological features do tend to be slightly more acidic than their surroundings according to the literature (see Chapter 2). This represents a change in hydrogen ion concentration, which means that a similar number of free electrons and ions exist in the soil, either on the surfaces of crystal structures such as kaolinite (the potential-determining ions) or as mobile charges in the soil solution. Electrical potential changes with pH because the potential-determining ions have variable surface charge density depending on the concentration of H^+ and OH^- , and these determine the ionic distribution of the soil solution (White 1987, 97). This combination of changing ionic concentrations of elements then, together with the oxidation states of the soils are the most likely cause of correlating geophysical and crop responses to archaeologically altered subsurface conditions. In Table 6.29 it can be seen that Mn concentrations appear to have similar patterns of enrichment and depletion in the various features. In environments of changing oxidation state the redox equilibrium of Fe is likely to be affected by drainage and the behaviour of soil moisture within the individual contexts. Under these circumstances Fe and Mn are in competition in the soil for electrons as they are both transition elements that can exist in 2 and, in the case of Mn, 3, different valencies (Dr D Sanderson pers comm., see Chapter 2 for a full discussion). It is likely that the changes to the Fe chemistry have the largest effect on soil magnetism at the Case Studies. Changing ionic concentrations will also affect the ability of the soil solution to conduct electrical charge, so this situation also provides an explanation for the resistivity survey results, with resistance varying not just with water content, but also with the pH and E_h of that solution. So unlike the magnetic and crop responses, resistivity is less likely to respond to the changing concentrations of

individual elements specifically, but instead it is likely to change with electrical (obviously) and redox potential. Many of the compounds within the soil are pH and redox dependent. The element suggested to be predominantly responsible for the production of differential growth due to changing redox potential is Fe (W Fricke pers comm.). This leads to a consideration of the elemental composition of the plants measured during ICP-MS analysis.

Although the plants grown in excavated contexts from Case Study 1 do not represent the exact field situation or represent the combination of stratigraphic layers involved in geophysical sampling and crop mark development, the experimental results in Chapter 6 show that there is reasonable statistical correlation between the properties of augured and excavated soils, so these differences will be ignored in the following discussions of plant growth and development under glasshouse conditions. Unfortunately the uptake of several elements can not be discussed because the results of the analyses were invalid. For these elements some negative values were recorded which indicates that at some point during the analysis the samples became contaminated (Dr D P Moss pers comm.). These elements include Mo, Cd, Co, Ti, Ni and P, the latter being most unfortunate given its application to archaeological geochemical sampling. The data are divided into analysis of plants grown in archaeological soils, and those grown in composts in Tables 6.29 b and c respectively (Chapter 6). The compost grown plants showed a high degree of changes in concentration in response to changing watering regimes and altered soil depths. Elements that showed statistically significant variations due to these cultural conditions included Cu, K, Zn, Cr and S. As these concentration changes occurred in composts rather than archaeological soils, it suggests that they represent the 'soil chemical component' of crop mark responses. From the preceding discussion of elemental distributions within soil samples it is clear that many of the altered concentrations of elements in plants are significantly affected by the redox potential of the soil, for example in Experiment 4 Cu, K, Zn and S were depleted in waterlogged plants and had high concentrations in plants that had been droughted. Alteration of the elemental compositions was also noticeable because of changing soil depth, for example in Experiment 5 optimally watered plants grown in shallow soils were enhanced in S, but depleted in Zn, whereas in the droughted plants grown at the same soil depths Cu, Zn and S were enhanced with no evidence of elemental depletion in the harvested material.

Moving to the plants grown in archaeological soils, Case Study 2 plants displayed a larger range of elemental variations (Table 6.29b), and this was assumed to be due to the soil samples in

which the plants were grown being augured and so containing material from the topsoils and hopefully also the underlying archaeological features. However, statistical analysis of the data revealed only Mg, Mn, Zn, Al and Fe to vary significantly between features, with Fe and the associated Mn being of most interest to this discussion, being implicated in the development of the magnetic anomalies. At Case study 2 it is likely that those elements seen to vary significantly between features in the plants analysed that have importance for the remotely sensed data include Mg, Mn, Al and Fe, with variations in Zn being more likely to be attributable to water-related uptake on the basis of Experiments 4 and 5 results. Mg was significantly higher in plants grown in ditch soils, whilst Al and Fe were depleted in plants grown in inter-ditch soils, with higher concentrations of Mn found in plants grown from soils from the enclosure interior.

Moving to the plants grown in excavated soils from Case Study 1, there are several elements which were shown to change significantly between features. These include Ca, Cu, Mg, Mn, Na and to a lesser extent Fe and Zn. The larger numbers of elements contributing significantly towards the elemental composition in the individual features is in part a consequence of having changed watering regimes for plants from each context. Again, on the basis of Experiments 4 and 5, several of these elements can be ruled out as changing due to anthropogenic inputs, leaving Ca, Mg, Mn, Na and to a lesser extent Fe as ones likely to contribute to the remotely sensed results for the site. Elements that changed significantly at this site due to watering regime differences were Fe, which was enhanced in plants grown in waterlogged ditch soils, and K, which was present in higher concentrations in plants grown in droughted ditch soils. Again this points to the importance of redox reactions in the soil for the enhancement of elemental differences present.

Table 7.2: Variations In Concentrations of Fe, Cu, and Ti

Case Study	General On-site Enhancement	Exterior/ Topsoil		Ditch/fills		Bank/ Reverse Anomaly High	Interior High	Natural	
		High	Low	High	Low			High	Low
1 Excavated			Fe		Fe Cu Ti			Ti	
1 Augured			Fe	Fe* Cu* Ti*		Cu Fe Ti reverse anomaly; Fe Ti bank			
2	Fe Cu		Fe	Cu Fe Ti			Cu Fe		
3		Cu			Fe Ti Cu			Ti	Cu

*Higher relative to excavated samples but still relatively depleted

Comparison of the soil and plant data in Table 6.29 shows that for the ditches there is correlation between the high concentrations of Cu, Fe, Na and Mg, but where K and Mn were also enhanced in the soils, they appear to be relatively depleted in the plants, suggesting that the former were either taken up preferentially during plant growth, or that the latter were relatively very enhanced, or unavailable to plants in the form that they existed in the ditch soils. There are mechanisms that are growth rate related by which plants control uptake and use of individual elements (Marschner 1995, 52-62).

To conclude this section, the chemistry of Fe compounds is revisited, this time with regard to its uptake by plants. Drainage is likely to impact on the oxidation state of Fe, which affects its availability to plants. Ferric (Fe (III)) compounds can be fixed as ferric-oxyhydroxides and be less available to plants, and these compounds also absorb trace elements, which could result in a general trace element deficiency, specifically involving Fe, Mn, Zn, Cu, Mo, B and Cl (Dr Allan Hall pers comm.). In soils Fe tends to exist mainly as colloidal ferric (Fe(III)) oxides such as haematite (Fe_2O_3) under aerobic conditions, which tend to be partly stabilised by organic matter and adsorption on clay minerals. Where there is much organic matter the Fe may be reduced to the ferrous state (Fe(II)) and exist in the soil solution or as complexes adsorbed upon other surfaces. Generally however Fe(III) compounds are the main forms of soluble Fe in soil and nutrient solutions, although Fe(II) compounds are also present (Marschner 1995, 313).

In most plants Fe(II) is taken up in preference to Fe(III), although this is species dependent.. In barley species the plants have a mechanism for preferential uptake of Fe(III), and for oxidising Fe(II) compounds in the absence of Fe(III) supplies. This mechanism also allows transport of other heavy metals such as Zn, Cu and Mn; although they are not as easily translocated once they have entered the plant roots (Marschner 1995, 60). This raises the interesting question of whether magnetic anomalies exist partly within the vegetation canopy at individual sites (W Fricke and Dr D Sanderson pers comm., see Chapter 2), and whether uptake by particularly barley, but also by other graminaceous plants, causes a partitioning in the soil-plant system of magnetite and haematite respectively, although the dynamic equilibrium of the soil system probably compensates for this. Initial investigations into this phenomenon were initiated during the summer of 2004, when a site in the UCVLP area (Plate 4.6, Chapter 4) that had been partially stripped of vegetation and topsoil was examined magnetically. The data from this survey is awaiting analysis. In addition to this, it has been suggested that the crop mark above

the site at Case study 1 is at least in part a consequence of this preferential uptake of Fe(III), which given the propensity of the site to be waterlogged in the interior at least, would fit with the field observations, and would also fit with the observed reversed magnetic results recorded there.

7.5 What Is The Significance Of This Approach For Future Prospection Methodologies?

In this thesis the combined use of geochemical and remotely sensed data allows more to be said about the reasons for the responses rather than providing an anthropogenic explanation of the site. It highlights specifically the problems that variations in soil chemical environments bring about when generalising about remotely sensed data during archaeological interpretations of sites, and it also highlights the role of experience and archaeological knowledge in the interpretations made. For example, purely on the basis of the resistivity data, enclosure 2 at Case study 2 would be interpreted as being defined by a bank rather than a ditch, and similarly the features of the enclosure at Case study 1 would be interpreted as ditch and bank rather than bank and ditch on the basis of the magnetic anomalies, but a background knowledge of this and the surrounding sites in the area, together with the magnetic and aerial information leads to the enclosure being interpreted as ditch-defined. Attention to the reasons for these reversed anomalies has the potential to provide a better understanding of site conditions, and has also provided here the means to assess which variations in elemental composition are responsible for the remotely sensed responses.

7.6 Conclusions and Recommendations For Future Work

Before anything can be taken from this thesis it is clear that many more sites must be examined geochemically in an attempt to build a database of responses to the elemental variations at the sites with reference to the remotely sensed data. This kind of work is becoming increasingly more common within archaeological circles, as a conference held at Glasgow University Archaeology Department in summer 2003 highlighted (Jones and Sharpe in prep; Wilson *et al* in prep; Entwistle *et al* in prep), but it tends to be confined to the determination of marker elements for historical sites rather than encompassing all prospection techniques and periods. The combination of these approaches has the potential to provide an extremely powerful, mostly non-

invasive (although it still requires the procurement of soil samples and some amount of ‘ground truthing’) tool for understanding structural (geophysical and aerial) and functional (geochemical) areas of sites.

In many ways this thesis is based on a very superficial treatment of what is a very complicated set of factors and data collected in response to them. For this reason it is seen as a starting point for future research. Because it is so multi-disciplinary the most efficient way forward would be to have a collaborative research effort that involved archaeologists, including those that specialise in aerial reconnaissance and geophysical survey, who in tandem with people with expertise in soil science, statistical analysis of multivariate data, plant and agricultural chemistry, could tease out the reasons for the responses to the buried archaeological remains to best effect.

In terms of the research undertaken here, the limited pot-based experiments suggest that aerial photographic interpretations are perhaps an over-simplification of the ground conditions. The results presented suggest that a more thorough interpretation could be secured if the crop mark is investigated less superficially, as discussed in previous chapters. Additionally it must be remembered that an aerial photograph is literally a snapshot of a site on a specific day, and the development of growth characteristics during the growing season tends to confirm the requirement for continued reconnaissance and recording at individual sites to allow the fullest interpretations to be made as suggested by Scollar *et al* (1990, 51-2). He suggests, and the growth experiments tend to confirm, that definitive detailed interpretations cannot be made unless there are a full set of prints available to follow crop development. This type of strategy, in conjunction with increased use of colour photography to develop a database of the range of hues of green present for example to examine water stress responses more fully, particularly in conjunction with geophysical and geochemical data, is likely ultimately to yield site information approaching the detail of that available for excavated sites, albeit without the important contribution of datable evidence taken from artefacts.

Although the research has identified certain elements that appear to indicate ditches and other features comprising the Case Studies, it has not produced definitive answers that would allow someone to now go out into the field and sample for one particular element secure in the knowledge that if found at altered concentrations the spot where the sample was taken could categorically be said to overly an enclosure ditch. Although this would have been a fantastic

way to summarise the thesis, it was always clear that soil chemistry and all the other variables involved in producing crop marks and geophysical responses, and also in the preservation of the archaeological remains heavily weighed against this being accomplished. However, the combined analysis of ionic concentrations and oxidation states in soils and plants comprising an archaeological site have been shown to be the most likely common denominator in the development of all three remotely sensed techniques considered here.

In the short-term an extension of the examination of the responses observed during the glasshouse experiments into a field-based setting would be a good way to move this research forward. Anticipated future work is likely to focus on the measurement of conductivity, E_h and pH of soils and pore waters in field situations (Dr D Sanderson pers comm.), together with a more detailed look at Fe chemistry, which appears to be the element with the most potential for positively and definitively linking the three techniques. Finally, a more detailed examination of electromagnetic effects in the soil and soil solution would be very informative, as contributions to the magnetic anomalies measured during field survey from this component would effectively mean that archaeological anomalies were not simply due to the presence of Fe compounds with higher magnetic susceptibilities, as was discussed briefly in Chapter 2, but to consider this fully would need the addition of a physicist to the multidisciplinary team.

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Experiment 1: Groundwater Levels and Soil Temperature Measured in the Fosse Way																	
Station 1					Station 2					Station 3					Soil Temperature		Soil Depth (cm)
Year	Month	Day	Time	Soil Temp (°C)	Year	Month	Day	Time	Soil Temp (°C)	Year	Month	Day	Time	Soil Temp (°C)	Air Temp (°C)		
1979	7	15	10.00	10.5	1979	7	15	10.00	10.5	1979	7	15	10.00	10.5	17.5	17.5	
1979	7	15	10.30	10.5	1979	7	15	10.30	10.5	1979	7	15	10.30	10.5	17.5	17.5	
1979	7	15	11.00	10.5	1979	7	15	11.00	10.5	1979	7	15	11.00	10.5	17.5	17.5	
1979	7	15	11.30	10.5	1979	7	15	11.30	10.5	1979	7	15	11.30	10.5	17.5	17.5	
1979	7	15	12.00	10.5	1979	7	15	12.00	10.5	1979	7	15	12.00	10.5	17.5	17.5	
1979	7	15	12.30	10.5	1979	7	15	12.30	10.5	1979	7	15	12.30	10.5	17.5	17.5	
1979	7	15	13.00	10.5	1979	7	15	13.00	10.5	1979	7	15	13.00	10.5	17.5	17.5	
1979	7	15	13.30	10.5	1979	7	15	13.30	10.5	1979	7	15	13.30	10.5	17.5	17.5	
1979	7	15	14.00	10.5	1979	7	15	14.00	10.5	1979	7	15	14.00	10.5	17.5	17.5	
1979	7	15	14.30	10.5	1979	7	15	14.30	10.5	1979	7	15	14.30	10.5	17.5	17.5	
1979	7	15	15.00	10.5	1979	7	15	15.00	10.5	1979	7	15	15.00	10.5	17.5	17.5	
1979	7	15	15.30	10.5	1979	7	15	15.30	10.5	1979	7	15	15.30	10.5	17.5	17.5	
1979	7	15	16.00	10.5	1979	7	15	16.00	10.5	1979	7	15	16.00	10.5	17.5	17.5	
1979	7	15	16.30	10.5	1979	7	15	16.30	10.5	1979	7	15	16.30	10.5	17.5	17.5	
1979	7	15	17.00	10.5	1979	7	15	17.00	10.5	1979	7	15	17.00	10.5	17.5	17.5	
1979	7	15	17.30	10.5	1979	7	15	17.30	10.5	1979	7	15	17.30	10.5	17.5	17.5	
1979	7	15	18.00	10.5	1979	7	15	18.00	10.5	1979	7	15	18.00	10.5	17.5	17.5	
1979	7	15	18.30	10.5	1979	7	15	18.30	10.5	1979	7	15	18.30	10.5	17.5	17.5	
1979	7	15	19.00	10.5	1979	7	15	19.00	10.5	1979	7	15	19.00	10.5	17.5	17.5	
1979	7	15	19.30	10.5	1979	7	15	19.30	10.5	1979	7	15	19.30	10.5	17.5	17.5	
1979	7	15	20.00	10.5	1979	7	15	20.00	10.5	1979	7	15	20.00	10.5	17.5	17.5	
1979	7	15	20.30	10.5	1979	7	15	20.30	10.5	1979	7	15	20.30	10.5	17.5	17.5	
1979	7	15	21.00	10.5	1979	7	15	21.00	10.5	1979	7	15	21.00	10.5	17.5	17.5	
1979	7	15	21.30	10.5	1979	7	15	21.30	10.5	1979	7	15	21.30	10.5	17.5	17.5	
1979	7	15	22.00	10.5	1979	7	15	22.00	10.5	1979	7	15	22.00	10.5	17.5	17.5	
1979	7	15	22.30	10.5	1979	7	15	22.30	10.5	1979	7	15	22.30	10.5	17.5	17.5	
1979	7	15	23.00	10.5	1979	7	15	23.00	10.5	1979	7	15	23.00	10.5	17.5	17.5	
1979	7	15	23.30	10.5	1979	7	15	23.30	10.5	1979	7	15	23.30	10.5	17.5	17.5	
1979	7	15	24.00	10.5	1979	7	15	24.00	10.5	1979	7	15	24.00	10.5	17.5	17.5	
1979	7	15	24.30	10.5	1979	7	15	24.30	10.5	1979	7	15	24.30	10.5	17.5	17.5	
1979	7	15	25.00	10.5	1979	7	15	25.00	10.5	1979	7	15	25.00	10.5	17.5	17.5	
1979	7	15	25.30	10.5	1979	7	15	25.30	10.5	1979	7	15	25.30	10.5	17.5	17.5	
1979	7	15	26.00	10.5	1979	7	15	26.00	10.5	1979	7	15	26.00	10.5	17.5	17.5	
1979	7	15	26.30	10.5	1979	7	15	26.30	10.5	1979	7	15	26.30	10.5	17.5	17.5	
1979	7	15	27.00	10.5	1979	7	15	27.00	10.5	1979	7	15	27.00	10.5	17.5	17.5	
1979	7	15	27.30	10.5	1979	7	15	27.30	10.5	1979	7	15	27.30	10.5	17.5	17.5	
1979	7	15	28.00	10.5	1979	7	15	28.00	10.5	1979	7	15	28.00	10.5	17.5	17.5	
1979	7	15	28.30	10.5	1979	7	15	28.30	10.5	1979	7	15	28.30	10.5	17.5	17.5	
1979	7	15	29.00	10.5	1979	7	15	29.00	10.5	1979	7	15	29.00	10.5	17.5	17.5	
1979	7	15	29.30	10.5	1979	7	15	29.30	10.5	1979	7	15	29.30	10.5	17.5	17.5	
1979	7	15	30.00	10.5	1979	7	15	30.00	10.5	1979	7	15	30.00	10.5	17.5	17.5	
1979	7	15	30.30	10.5	1979	7	15	30.30	10.5	1979	7	15	30.30	10.5	17.5	17.5	
1979	7	15	31.00	10.5	1979	7	15	31.00	10.5	1979	7	15	31.00	10.5	17.5	17.5	
1979	7	15	31.30	10.5	1979	7	15	31.30	10.5	1979	7	15	31.30	10.5	17.5	17.5	
1979	7	15	32.00	10.5	1979	7	15	32.00	10.5	1979	7	15	32.00	10.5	17.5	17.5	
1979	7	15	32.30	10.5	1979	7	15	32.30	10.5	1979	7	15	32.30	10.5	17.5	17.5	
1979	7	15	33.00	10.5	1979	7	15	33.00	10.5	1979	7	15	33.00	10.5	17.5	17.5	
1979	7	15	33.30	10.5	1979	7	15	33.30	10.5	1979	7	15	33.30	10.5	17.5	17.5	
1979	7	15	34.00	10.5	1979	7	15	34.00	10.5	1979	7	15	34.00	10.5	17.5	17.5	
1979	7	15	34.30	10.5	1979	7	15	34.30	10.5	1979	7	15	34.30	10.5	17.5	17.5	
1979	7	15	35.00	10.5	1979	7	15	35.00	10.5	1979	7	15	35.00	10.5	17.5	17.5	
1979	7	15	35.30	10.5	1979	7	15	35.30	10.5	1979	7	15	35.30	10.5	17.5	17.5	
1979	7	15	36.00	10.5	1979	7	15	36.00	10.5	1979	7	15	36.00	10.5	17.5	17.5	
1979	7	15	36.30	10.5	1979	7	15	36.30	10.5	1979	7	15	36.30	10.5	17.5	17.5	
1979	7	15	37.00	10.5	1979	7	15	37.00	10.5	1979	7	15	37.00	10.5	17.5	17.5	
1979	7	15	37.30	10.5	1979	7	15	37.30	10.5	1979	7	15	37.30	10.5	17.5	17.5	
1979	7	15	38.00	10.5	1979	7	15	38.00	10.5	1979	7	15	38.00	10.5	17.5	17.5	
1979	7	15	38.30	10.5	1979	7	15	38.30	10.5	1979	7	15	38.30	10.5	17.5	17.5	
1979	7	15	39.00	10.5	1979	7	15	39.00	10.5	1979	7	15	39.00	10.5	17.5	17.5	
1979	7	15															

Appendix 1 Growth Characteristics

All concentrations given in all appendices are for elements (not compounds) and are in p.p.m.

Experiment 2: Germination Rates and Soil Temperatures Measured in the Plant Pots

Week 1				Week 2					Week 3			% Germination				Soil Temperature, C
Pot No	No Seeds	Germination	% Germination	No Seeds	Germination.	New Seeds	Total Germination	% Germination	No Seeds	New Seeds	total Germination	Wk1	Wk2	Wk3	Total	
1	6	3	50.0	3	6	3	6	100.0	3	0	6	50.0	100.0	100.0	100.0	28
2	9	2	22.2	2	5	3	5	55.6	3	3	8	22.2	55.6	88.9	88.9	28
3	8	1	12.5	1	2	1	2	25.0	3	0	2	12.5	25.0	25.0	25.0	29
4	9	5	55.6	5	7	2	7	77.8	3	2	9	55.6	77.8	100.0	100.0	29
5	7	5	71.4	5	6	1	6	85.7	3	0	6	71.4	85.7	85.7	85.7	29
6	8	4	50.0	4	6	2	6	75.0	3	1	7	50.0	75.0	87.5	87.5	29
7	8	5	62.5	5	7	2	7	87.5	3	0	7	62.5	87.5	87.5	87.5	29
8	8	1	12.5	1	5	4	5	62.5	3	0	5	12.5	62.5	62.5	62.5	28
9	7	7	100.0	5	5	0	7	100.0	3	0	7	100.0	100.0	100.0	100.0	28
10	8	7	87.5	5	6	1	8	100.0	3	0	8	87.5	100.0	100.0	100.0	30
11	7	6	85.7	5	6	1	7	100.0	3	0	7	85.7	100.0	100.0	100.0	30
12	8	7	87.5	5	6	1	8	100.0	3	0	8	87.5	100.0	100.0	100.0	30
13	9	4	44.4	4	8	4	8	88.9	3	0	8	44.4	88.9	88.9	88.9	26
14	7	6	85.7	5	6	1	7	100.0	3	0	7	85.7	100.0	100.0	100.0	26
15	8	5	62.5	5	5	0	5	62.5	3	2	7	62.5	62.5	87.5	87.5	27
16	9	8	88.9	5	6	1	9	100.0	3	0	9	88.9	100.0	100.0	100.0	27
17	9	5	55.6	5	6	1	6	66.7	3	0	6	55.6	66.7	66.7	66.7	28
18	8	4	50.0	4	4	0	4	50.0	3	0	4	50.0	50.0	50.0	50.0	29
19	7	5	71.4	5	6	1	6	85.7	3	0	6	71.4	85.7	85.7	85.7	26
20	8	5	62.5	5	6	1	6	75.0	3	0	6	62.5	75.0	75.0	75.0	26
21	11	10	90.9	5	5	0	10	90.9	3	0	10	90.9	90.9	90.9	90.9	27
22	8	6	75.0	5	7	2	8	100.0	3	0	8	75.0	100.0	100.0	100.0	28
23	7	3	42.9	3	4	1	4	57.1	3	1	5	42.9	57.1	71.4	71.4	28
24	8	5	62.5	5	6	1	6	75.0	3	1	7	62.5	75.0	87.5	87.5	29
25	9	4	44.4	4	6	2	6	66.7	3	1	7	44.4	66.7	77.8	77.8	26
26	9	5	55.6	5	7	2	7	77.8	3	0	7	55.6	77.8	77.8	77.8	26
27	7	5	71.4	5	6	1	6	85.7	3	0	6	71.4	85.7	85.7	85.7	28
28	9	3	33.3	3	7	4	7	77.8	3	0	7	33.3	77.8	77.8	77.8	29
29	8	7	87.5	5	5	0	7	87.5	3	0	7	87.5	87.5	87.5	87.5	29
30	11	9	81.8	5	7	2	11	100.0	3	0	11	81.8	100.0	100.0	100.0	29.5
31	9	4	44.4	4	5	1	5	55.6	3	2	7	44.4	55.6	77.8	77.8	25
32	10	5	50.0	5	9	4	9	90.0	3	1	10	50.0	90.0	100.0	100.0	27
33	11	8	72.7	5	8	3	11	100.0	3	0	11	72.7	100.0	100.0	100.0	28
34	8	5	62.5	5	7	2	7	87.5	3	0	7	62.5	87.5	87.5	87.5	30
35	9	8	88.9	5	6	1	9	100.0	3	0	9	88.9	100.0	100.0	100.0	31

Experiment 2: Germination Rates and Soil Temperatures Measured in the Plant Pots (cont)

Week 1				Week 2					Week 3			% Germination				Soil Temperature, C
Pot No	No Seeds	Germination	% Germination	No Seeds	Germination.	New Seeds	Total Germination	% Germination	No Seeds	New Seeds	total Germination	Wk1	Wk2	Wk3	Total	
36	10	5	50.0	5	8	3	8	80.0	3	2	10	50.0	80.0	100.0	100.0	30
37	10	2	20.0	2	5	3	5	50.0	3	3	8	20.0	50.0	80.0	80.0	26
38	10	4	40.0	4	8	4	8	80.0	3	0	8	40.0	80.0	80.0	80.0	28
39	8	4	50.0	4	5	1	5	62.5	3	2	7	50.0	62.5	87.5	87.5	27
40	9	4	44.4	4	9	5	9	100.0	3	0	9	44.4	100.0	100.0	100.0	28
41	10	4	40.0	4	9	5	9	90.0	3	1	10	40.0	90.0	100.0	100.0	29
42	9	6	66.7	5	7	2	8	88.9	3	1	9	66.7	88.9	100.0	100.0	29
43	8	6	75.0	5	6	1	7	87.5	3	0	7	75.0	87.5	87.5	87.5	27

Experiment 2: Leaf Heights and Numbers of Leaves

Pot No	Feature	Average Leaf Heights	Number of Leaves
9	Control	10.17	19
27	Enclosure exterior	7.34	12
31	Enclosure exterior	5.67	10
6	Outer ditch, reverse anomaly/bank	1.27	10
16	Outer ditch, reverse anomaly/bank	5.66	11
23	Outer ditch	6.80	12
24	Outer ditch	10.70	12
1	Inter-ditch	4.87	10
3	Inter-ditch	0.00	9
4	Inter-ditch	2.03	11
12	Inter-ditch	6.65	10
15	Inter-ditch	9.93	11
26	Inter-ditch	4.98	10
28	Inter-ditch	7.35	10
30	Inter-ditch	4.38	10
32	Inter-ditch	4.75	8
36	Inter-ditch	9.70	9
38	Inter-ditch	4.88	12
40	Inter-ditch	4.80	9
5	Internal ditch	6.26	11
7	Internal ditch	5.44	9
8	Internal ditch	0.00	7
10	Internal ditch	5.33	10

Experiment 2: Leaf Heights and Numbers of Leaves (cont)

Pot No	Feature	Average Leaf Heights	Number of Leaves
14	Internal ditch	5.26	9
22	Internal ditch	9.42	12
25	Internal ditch	10.70	9
43	Internal ditch	7.23	14
2	Interior ditch at branch point	2.80	9
33	Interior ditch at branch point	5.81	11
11	Interior	3.95	8
13	Interior	7.40	10
17	Interior	6.46	12
18	Interior	10.05	13
19	Interior	9.95	12
20	Interior	9.73	11
21	Interior	6.23	11
29	Interior	8.51	11
34	Interior	6.70	10
35	Interior	6.15	12
37	Interior	0.00	9
39	Interior	6.87	9
41	Interior	7.23	11
42	Interior	5.67	11

Experiment 2: Soil Properties

Pot No	Feature	pH	Conductivity, Siemens	Soil temperature, C
9	Control	6.93	46	28.0
37	Interior	6.22	45	26.0
11	Interior	5.77	29	30.0
41	Interior	6.23	45	29.0
34	Interior	6.31	54	30.0
35	Interior	6.16	48	31.0
13	Interior	6.43	52	26.0
20	Interior	5.77	55	26.0
17	Interior	6.26	36	28.0
18	Interior	6.55	48	29.0
19	Interior	6.84	29	26.0
21	Interior	6.11	35	27.0
29	Interior	5.96	68	29.0

Experiment 2: Soil Properties (cont)

Pot No	Feature	pH	Conductivity, Siemens	Soil temperature, C
39	Interior	5.94	82	27.0
42	Interior	6.50	59	29.0
2	Ditch	6.02	129	28.0
8	Ditch	6.17	156	28.0
24	Ditch	6.81	48	29.0
6	Ditch	6.00	53	29.0
23	Ditch	6.79	44	28.0
33	Ditch	6.05	48	28.0
43	Ditch	6.91	49	27.0
7	Ditch	6.12	20	29.0
25	Ditch	6.70	104	26.0
10	Ditch	6.25	35	30.0
14	Ditch	6.29	45	26.0
16	Ditch	6.00	42	27.0
22	Ditch	6.51	50	28.0
5	Ditch	6.81	36	29.0
3	Inter-ditch	5.61	0	29.0
12	Inter-ditch	6.11	68	30.0
30	Inter-ditch	5.70	43	29.5
1	Inter-ditch	6.38	37	28.0
15	Inter-ditch	6.52	36	27.0
28	Inter-ditch	6.24	68	29.0
32	Inter-ditch	6.37	63	27.0
36	Inter-ditch	5.99	85	30.0
38	Inter-ditch	5.92	79	28.0
4	Inter-ditch	6.53	30	29.0
40	Inter-ditch	6.76	77	28.0
26	Inter-ditch	6.64	47	26.0
31	Exterior	6.44	45	25.0
27	Exterior	6.62	84	28.0

Experiment 2: Leaf Areas

Pot No	Feature	Mean Leaf Area, cm ²
9	Control	117.1
37	Interior	23.5
11	Interior	30.9
41	Interior	34.1
34	Interior	26.8
35	Interior	38.1
13	Interior	43.7
20	Interior	38.2
17	Interior	32.6
18	Interior	38.3
19	Interior	38.1
21	Interior	31.9
29	Interior	36.6
39	Interior	40.6
42	Interior	30.5
2	Ditch	26.5
8	Ditch	25.2
24	Ditch	38.7
6	Ditch	31.2
23	Ditch	42.0
33	Ditch	39.4
43	Ditch	30.3
7	Ditch	27.2
25	Ditch	25.9
10	Ditch	27.3
14	Ditch	21.1
16	Ditch	43.5
22	Ditch	36.1
5	Ditch	31.5
3	Inter-ditch	29.2
12	Inter-ditch	33.1
1	Inter-ditch	28.7
30	Inter-ditch	43.9
15	Inter-ditch	36.3
28	Inter-ditch	24.7
32	Inter-ditch	16.1

Experiment 2: Leaf Areas (cont)

Pot No	Feature	Mean Leaf Area, cm ²
36	Inter-ditch	38.6
38	Inter-ditch	32.2
4	Inter-ditch	34.6
40	Inter-ditch	33.4
26	Inter-ditch	36.0
31	Exterior	35.1
27	Exterior	38.6

Experiment 2: Progress of Growth During Experimental Work

Pot No	Feature	15 May	29 May		
		Average Height, cm	Average Height, cm	Average No Leaves	Average No Tillers
9	Control	10.17	34.67	6.33	1.33
37	Interior	0.00	17.93	3.00	0.00
11	Interior	3.95	21.93	2.67	0.00
41	Interior	7.23	22.97	3.67	0.00
34	Interior	6.70	20.50	3.33	0.00
35	Interior	6.15	21.83	4.00	0.00
13	Interior	7.40	22.53	3.33	0.00
20	Interior	9.73	21.67	3.67	0.00
17	Interior	6.46	20.00	4.00	0.00
18	Interior	10.05	21.10	3.00	0.00
19	Interior	9.95	22.67	4.00	0.00
21	Interior	6.23	17.50	3.67	0.00
29	Interior	8.51	21.33	3.67	0.00
39	Interior	6.87	21.57	3.00	0.00
42	Interior	5.67	18.43	3.67	0.00
2	Ditch	2.80	18.77	3.00	0.00
8	Ditch	0.00	18.90	2.33	0.00
24	Ditch	10.70	24.83	4.00	0.00
6	Ditch	1.27	20.03	3.33	0.00
23	Ditch	6.80	21.40	4.00	0.00
33	Ditch	5.81	20.80	3.67	0.00
43	Ditch	7.23	19.43	4.67	0.00
7	Ditch	5.44	21.23	3.00	0.00
25	Ditch	10.70	21.70	3.00	0.00

Experiment 2: Progress of Growth During Experimental Work (cont)

Pot No	Feature	15 May	29 May		
		Average Height, cm	Average Height, cm	Average No Leaves	Average No Tillers
10	Ditch	5.33	18.63	3.33	0.00
14	Ditch	5.26	18.07	3.00	0.00
16	Ditch	5.66	24.17	3.67	0.00
22	Ditch	9.42	22.10	4.00	0.00
5	Ditch	6.26	20.90	3.67	0.00
3	Inter-ditch	0.00	17.40	3.00	0.00
12	Inter-ditch	6.65	21.67	3.33	0.00
1	Inter-ditch	4.87	17.20	3.33	0.00
30	Inter-ditch	4.38	23.07	3.33	0.00
15	Inter-ditch	9.93	21.87	3.67	0.00
28	Inter-ditch	7.35	19.47	3.33	0.00
32	Inter-ditch	4.75	18.87	2.67	0.00
38	Inter-ditch	4.88	20.40	4.00	0.00
4	Inter-ditch	2.03	19.43	3.67	0.00
40	Inter-ditch	4.80	20.57	3.00	0.00
26	Inter-ditch	4.98	19.73	3.33	0.00
31	Exterior	5.67	19.90	3.33	0.00
27	Exterior	7.34	22.83	4.00	0.00

Experiment 2: Wet and Dry Weights at Harvest

Pot No	Feature	Wet Weight, g	Dry Weight, g
9	Control	6.9	1.4
37	Interior	1.1	0.2
11	Interior	1.5	0.3
41	Interior	1.7	0.3
34	Interior	1.4	0.4
35	Interior	1.7	0.5
13	Interior	1.9	0.4
20	Interior	1.8	0.4
17	Interior	1.4	0.3
18	Interior	1.8	0.5
19	Interior	1.8	0.3
21	Interior	1.3	0.2
29	Interior	1.5	0.3

Experiment 2: Wet and Dry Weights at Harvest (cont)

Pot No	Feature	Wet Weight, g	Dry Weight, g
39	Interior	1.9	0.1
42	Interior	1.5	0.3
2	Ditch	1.2	0.2
8	Ditch	1.3	0.2
24	Ditch	2.0	0.5
6	Ditch	1.6	0.3
23	Ditch	1.7	0.4
33	Ditch	1.4	0.2
43	Ditch	1.5	0.4
7	Ditch	1.7	0.3
25	Ditch	1.7	0.2
10	Ditch	1.2	0.2
14	Ditch	1.0	0.2
16	Ditch	1.7	0.4
22	Ditch	1.7	0.4
5	Ditch	1.5	0.4
3	Inter-ditch	1.3	0.1
12	Inter-ditch	1.6	0.4
30	Inter-ditch	1.9	0.4
1	Inter-ditch	1.2	0.4
15	Inter-ditch	1.7	0.4
28	Inter-ditch	1.4	0.3
32	Inter-ditch	1.2	0.1
36	Inter-ditch	1.7	0.4
38	Inter-ditch	1.7	0.2
4	Inter-ditch	1.5	0
40	Inter-ditch	1.6	0.3
26	Inter-ditch	1.3	0.1
31	Exterior	1.7	0.4
27	Exterior	1.9	0.4

Experiment 3: Leaf Heights

Pot No	Watering Regime	Sample	Leaf Height, cm	Average Leaf Height, cm
43	Wet	Control	10.6	7.9
4	Optimum	Control	12.4	8.0
35	Dry	Control	11.7	9.3
36	Optimum	Topsoil	5.9	4.2
3	Dry	Topsoil	7.8	8.2
5	Wet	Topsoil	1.4	1.4
7	Dry	Topsoil	10.1	6.1
8	Wet	Topsoil	5.8	5.4
14	Dry	Topsoil	0.4	6.8
17	Optimum	Topsoil	5.1	5.1
41	Wet	Topsoil	7.5	8.2
20	Optimum	Topsoil	6.1	5.4
1	Dry	Ditch	10.5	6.0
6	Dry	Ditch	2.3	3.7
9	Wet	Ditch	0	0.0
10	Wet	Ditch	6.4	6.0
13	Wet	Ditch	2.7	2.9
15	Optimum	Ditch	4.4	7.6
18	Optimum	Ditch	5.4	7.8
19	Dry	Ditch	8.4	8.7
22	Optimum	Ditch	9.1	6.5
25	Optimum	Ditch	9.6	7.6
26	Wet	Ditch	11.4	8.4
27	Dry	Ditch	1.8	8.1
29	Dry	Ditch	9.6	9.6
31	Dry	Ditch	2.2	2.2
32	Wet	Ditch	2	5.7
33	Optimum	Ditch	2.1	1.8
34	Wet	Ditch	3.5	3.2
37	Optimum	Ditch	9.5	5.6
38	Wet	Ditch	4.5	4.7
39	Dry	Ditch	3.3	5.1
40	Wet	Ditch	4.5	3.8
42	Optimum	Ditch	11	10.8
46	Optimum	Ditch	0	0.0
47	Dry	Ditch	8.9	7.4
30	Optimum	Bank	1.1	0.9

Experiment 3: Leaf Heights (cont)

Pot No	Watering Regime	Sample	Leaf Height, cm	Average Leaf Height, cm
23	Dry	Bank	9.6	7.8
24	Wet	Bank	9.2	5.0
44	Optimum	Natural	2.3	1.3
45	Dry	Natural	2.8	3.3
48	Optimum	Natural	4.6	1.5
49	Optimum	Natural	2.1	3.1
50	Dry	Natural	2.7	3.9
51	Wet	Natural	6.4	6.8
2	Wet	Natural	9.1	6.9
11	Optimum	Natural	9.6	6.9
12	Dry	Natural	5.1	7.4
16	Wet	Natural	7.1	6.5
21	Dry	Natural	8.4	8.6
28	Wet	Natural	9	7.0

Experiment 3: Growth Characteristics

Pot No	Mean No Tillers	Mean No Leaves	Mean No Dead Leaves	Mean No Flowers	Mean Heights, cm	Wet Weight, g	Dry Weight, g	Loss on Drying, g
43	2.80	12.40	6.00	1.40	62.40	20.20	2.20	18.00
4	3.00	12.60	5.80	1.00	66.20	17.30	6.20	11.10
35	6.40	30.60	7.80	1.20	43.12	15.90	5.10	10.80
5	1.80	8.80	2.00	0.80	45.86	5.30	1.80	3.50
17	2.00	9.80	2.40	0.80	44.46	4.80	1.80	3.00
14	2.00	10.20	2.40	0.40	37.30	4.20	1.40	2.80
8	3.00	11.00	3.00	1.00	50.54	9.10	3.10	6.00
36	2.40	9.80	3.40	1.00	52.02	6.40	2.60	3.80
3	2.60	10.00	2.60	0.60	38.68	6.40	2.20	4.20
41	2.00	10.20	2.00	1.00	43.10	4.50	1.50	3.00
20	2.60	10.40	1.80	1.00	42.60	3.80	1.60	2.20
7	2.60	11.00	2.20	0.60	40.06	4.00	1.60	2.40
13	2.00	10.20	1.60	1.00	47.02	4.50	1.40	3.10
46	2.20	9.80	1.80	0.80	42.50	3.30	1.00	2.30
39	2.40	8.80	2.80	1.00	40.80	3.00	1.30	1.70
10	2.60	10.00	2.20	1.00	40.66	3.30	1.20	2.10
15	3.20	11.00	2.20	1.00	39.44	2.90	1.20	1.70
1	1.40	7.60	2.40	0.80	38.06	3.20	0.20	3.00
9	2.80	12.40	1.80	1.00	45.02	5.60	1.80	3.80
33	2.00	9.60	1.80	0.80	40.52	4.60	1.30	3.30
29	2.60	9.80	2.40	1.00	37.36	4.00	1.30	2.70

Experiment 3: Growth Characteristics (cont)

Pot No	Mean No Tillers	Mean No Leaves	Mean No Dead Leaves	Mean No Flowers	Mean Heights, cm	Wet Weight, g	Dry Weight, g	Loss on Drying, g
38	2.00	9.20	2.00	1.00	45.20	4.30	1.40	2.90
22	2.40	10.40	1.60	0.80	39.66	3.50	1.40	2.10
27	2.20	9.00	2.00	1.00	38.14	3.00	1.20	1.80
34	1.40	7.20	1.20	0.80	43.40	4.80	1.30	3.50
25	2.80	10.00	1.80	1.00	40.00	4.10	1.50	2.60
6	2.60	8.00	3.20	1.00	39.54	3.70	1.40	2.30
40	2.00	8.40	1.20	1.00	35.66	2.40	0.70	1.70
42	2.60	9.60	1.40	1.00	37.38	4.20	1.50	2.70
31	1.00	6.00	2.00	1.00	39.46	2.00	0.60	1.40
26	2.20	9.80	1.40	1.00	41.04	4.20	1.20	3.00
37	2.60	10.40	2.00	1.00	39.54	4.30	1.50	2.80
47	1.60	7.40	2.40	0.80	39.10	3.10	1.10	2.00
32	2.20	7.60	2.00	1.00	34.76	2.40	1.00	1.40
18	2.40	10.40	2.00	1.00	36.30	2.50	1.00	1.50
19	1.80	7.00	2.40	1.00	37.12	1.70	0.80	0.90
24	1.40	7.20	1.20	0.80	37.76	1.80	0.70	1.10
30	1.00	6.60	1.40	1.00	41.28	2.50	1.00	1.50
23	3.20	10.60	4.20	0.00	41.10	1.30	0.60	0.70
28	2.00	9.60	1.60	1.00	40.96	4.20	1.50	2.70
44	2.20	10.00	2.00	1.00	47.42	4.20	1.40	2.80
21	1.60	7.60	2.60	1.00	38.06	2.00	0.90	1.10
2	2.60	10.20	2.20	1.00	41.02	3.40	1.10	2.30
48	2.60	9.20	2.20	1.00	37.94	2.10	0.70	1.40
45	1.20	7.20	1.60	0.20	31.50	1.60	0.60	1.00
51	1.60	8.20	2.00	0.80	35.02	1.70	0.90	0.80
49	1.00	6.80	2.60	0.40	27.52	1.00	0.40	0.60
50	1.00	6.20	2.80	0.60	30.18	1.10	0.60	0.50
16	2.80	10.40	2.00	1.00	43.40	4.80	1.70	3.10
11	2.40	11.00	2.00	1.00	41.90	5.10	1.80	3.30
12	2.60	7.60	2.80	1.00	38.66	2.90	0.90	2.00

Experiment 4: Growth Characteristics at Harvest

Pot No	Watering Regime	Maximum Height, cm	No Tillers	No Leaves	Wet Weight, g
20	Optimum	50.8	70	264	129.8
22	Optimum	51.4	66	267	119.1
28	Optimum	44	55	206	77.2
37	Optimum	48.5	60	230	85.8
44	Optimum	44.7	59	220	95.9
53	Optimum	50.1	71	263	109.3

Experiment 4: Growth Characteristics at Harvest (cont)

Pot No	Watering Regime	Maximum Height, cm	No Tillers	No Leaves	Wet Weight, g
4	Droughted	29.6	44	144	40.3
11	Droughted	28.7	51	172	30.6
17	Droughted	3.2	46	161	26.2
34	Droughted	37.6	49	179	39.7
50	Droughted	45.4	54	206	85.3
54	Droughted	44.9	49	185	62.9
14	Waterlogged	35.2	53	198	53.2
19	Waterlogged	47.2	61	222	79.7
23	Waterlogged	46.9	58	214	68.7
35	Waterlogged	46.7	49	180	52.2
36	Waterlogged	45.8	47	173	49.2
51	Waterlogged	44.2	45	164	40.6

Experiment 4: Growth Characteristics at Harvest 2

Pot No	Watering Regime	Maximum Height, cm	No Tillers	No Leaves	No Dead Leaves	No Flowers	Wet weight, g
1	Optimum constant	49.1	83	409	40	2	184.8
9	Optimum constant	56	81	421	53	29	214.6
21	Optimum to dry	44	84	416	106	6	152.1
29	Optimum to dry	50.3	71	353	102	3	95.8
6	Optimum to wet	60.2	67	379	45	32	222.4
8	Optimum to wet	46.8	76	362	38	7	181.5
39	Dry constant	47.2	96	387	30	6	97.9
52	Dry constant	46.7	92	359	21	8	97.8
3	Dry to optimum	49.7	78	344	10	4	168.2
48	Dry to optimum	51.9	99	441	42	19	201.4
15	Dry to wet	49.8	79	351	26	5	149.4
24	Dry to wet	61.3	94	448	27	23	214.7
5	Wet constant	61.2	55	231	136	20	104.7
26	Wet constant	67.9	42	187	115	20	80.4
31	Wet to optimum	63.9	48	212	116	22	83
2	Wet to optimum	59.6	50	220	121	20	99.2
25	Wet to dry	65.7	47	204	105	19	74.7
49	Wet to dry	67.5	44	190	128	20	68.1

Experiment 4: Growth Characteristics at Harvest 3

Pot No	Watering Regime	Maximum Height, cm	No Tillers	No Flowers	Wet Weights, g
7	Optimum constant	68.8	76	53	107.7
16	Optimum constant	77.9	80	68	152.8
18	Optimum constant	77.2	85	69	127.2
27	Optimum constant	82	76	67	162.3
13	Optimum to dry	54.7	235	25	49.7
38	Optimum to wet	83.5	92	80	140.7
12	Dry constant	56.4	168	54	75.2
43	Dry constant	53.3	147	39	65.1
47	Dry constant	63.4	136	48	71.1
30	Dry to optimum	75.1	83	72	163.8
32	Dry to wet	61.4	76	88	145.7
42	Dry to wet	68.6	99	85	143.9
46	Wet constant	81.2	39	25	66.3
33	Wet constant	53.6	49	31	79.9
45	Wet to dry	72.7	24	20	25.9
10	Wet to dry	65	48	24	41

Experiment 4: Growth Characteristics at Harvest 3

Pot No	Watering Regime	Maximum Height, cm	No Tillers	No Flowers	Wet Weights, g
40	Wet to optimum	73.5	27	20	36.2
41	Wet to optimum	82	37	24	60.1

Experiment 5: Experimental Set-up

Pot no	Soil Depth, cm	Treatment
7	20	Optimum; shallow
4	40	Optimum; Medium
1	60	Optimum; deep
2	20	Wet; shallow
5	40	Wet; medium
6	60	Wet; deep
3	20	Dry; shallow
9	40	Dry; medium
8	60	Dry; deep

Experiment 5: Growth Characteristics

Pot No	Watering Regime	Week 1		Week 5	Harvest				
		No Seeds	No Germinated	Plants Flowering?	Maximum Height cm	No Dead Leaves	Colour	Growth Habit	Dry Weight, g
7	Optimum	200	71	N	145	c. 5%	Mid - dark green	Dense, uniform growth	170.4
4	Optimum	200	114	Y	149	Few	Dark green	Dense bushy canopy	265.2
1	Optimum	200	74	Y	153	<1%	Lush green	Uniform green bushy growth	329.3
2	Wet	200	133	Y	140	c. 50%	Mid - light green	Thin growth, minimal basal foliage	136.3
5	Wet	200	81	Y	144	c. 45%	Mid green	Less vigorous growth, few basal leaves	169.3
6	Wet	200	84	Y few	145	c. 50%	Dark green	Thin growth, minimal basal cover, darker green tops than basal portion	162.6
3	Dry	200	84	Y	117	Few	Very dark blue-green	Stunted growth, minimal basal foliage	105.1
9	Dry	200	92	Y	125	c. 50%	Dark green	Stunted growth, limited basal foliage	155.2
8	Dry	200	71	Y few	138	Very few	Mid - dark lush green	Lush uniform growth	199.7

Appendix 2: ICP-MS Analysis of Soil Samples

Case Study 1: Soil Analyses (Experiment 3), p.p.m. of Element

Sample No	Source	Al	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Ni	P	Pb	Ti	Zn	Na	S
41	Auger	18341.79	2206.16	2.06	9.16	38.07	11.02	19021.21	880.68	5174.40	282.45	24.54	965.68	23.65	458.75	43.37	97.85	562.22
42	Auger	20773.85	1884.86	2.85	15.60	47.48	14.69	28156.71	1287.30	8970.50	694.72	37.73	474.21	13.54	844.32	46.90	98.53	191.85
43	Auger	18298.28	2194.56	1.98	8.46	39.99	10.77	19270.13	847.23	4986.40	252.72	22.78	884.88	23.45	450.06	42.63	97.53	526.25
44	Excavated	15931.35	1247.66	2.20	11.71	36.83	13.23	25521.11	943.19	7460.90	424.13	27.32	410.80	8.76	1114.43	40.56	103.94	80.14
45	Auger	16796.14	1595.46	2.13	11.24	33.51	9.50	22496.58	993.38	6170.60	394.84	24.03	566.23	11.90	651.71	41.16	94.80	244.55
45R	Auger	17266.71	1529.56	2.47	10.93	34.84	9.62	23241.13	966.92	5935.10	409.07	25.30	582.38	11.99	661.29	39.26	83.98	265.46
48	Auger	16722.52	1458.56	1.90	7.75	33.03	9.74	18279.01	837.97	4651.90	213.95	20.35	689.35	18.17	455.78	37.43	63.51	398.06
50	Auger	17190.96	1033.16	1.86	7.82	32.42	7.84	17584.88	1063.20	4280.10	155.62	20.67	462.10	12.91	406.70	39.89	68.93	269.96
51	Auger	16464.60	1451.66	2.43	11.32	41.77	11.17	26479.83	893.47	5130.70	462.53	27.34	687.42	14.97	567.61	38.84	84.12	289.55
52	Auger	16793.91	1658.66	2.54	9.18	36.13	11.67	23231.40	880.06	5174.80	351.36	23.87	743.22	18.45	455.29	43.02	71.84	352.69
53	Excavated	17120.54	877.33	1.61	6.97	33.51	6.39	12686.49	734.12	4720.40	108.74	19.80	410.57	7.42	483.66	26.87	57.19	270.17
54	Auger	17993.85	1129.76	2.17	9.45	34.49	10.89	20365.28	925.47	5594.10	335.12	23.34	644.21	16.77	555.39	41.25	80.34	342.64
55	Auger	16757.94	1369.66	2.21	9.66	35.08	11.06	21114.09	890.94	5441.90	356.10	23.93	724.88	19.85	477.82	38.14	57.83	341.46
56	Excavated	17724.63	1022.76	2.01	10.21	37.31	8.86	22059.35	1903.90	4848.70	358.85	22.55	158.38	4.31	528.02	31.38	70.47	70.66
57	Auger	16939.35	1277.76	2.29	9.76	37.36	12.77	21897.05	881.13	5128.10	412.61	24.36	778.11	23.67	491.96	45.52	59.10	365.73
58	Auger	16838.20	1529.96	1.85	8.76	34.92	13.57	18525.65	879.07	4537.20	356.60	21.60	890.50	21.01	443.95	48.61	54.69	413.96
59	Auger	15547.25	1500.06	1.66	7.25	31.26	8.73	15713.00	870.83	4446.00	194.02	19.60	650.55	18.26	458.54	40.76	71.47	374.82

Case Study 1: Soil Analyses (Experiment 3), p.p.m. of Element (cont)

Sample No	Source	Al	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Ni	P	Pb	Ti	Zn	Na	S
60	Auger	15016.16	1113.26	2.31	14.54	30.68	10.55	24238.25	1083.50	6079.10	651.01	28.88	438.50	8.40	768.10	46.77	97.76	109.93
60R	Auger	15889.54	1068.76	2.31	14.46	33.50	12.70	24742.25	1147.70	6181.50	630.30	35.92	456.38	8.83	694.70	39.00	80.52	115.75
61	Auger	14919.00	1164.46	2.25	12.24	30.55	10.10	21338.70	1044.20	5944.80	493.99	26.71	443.35	9.89	670.57	36.20	97.78	155.94
62	Auger	16464.89	1793.16	2.06	7.62	34.31	10.22	17150.54	746.17	4461.10	314.88	19.94	900.97	19.91	409.42	43.65	57.03	412.26
63	Auger	17561.31	1374.06	1.97	7.75	34.67	9.36	17727.19	906.83	5087.00	216.97	22.30	622.68	12.31	503.88	37.80	67.33	344.50
64	Excavated	16706.98	1174.26	2.01	7.55	32.79	9.79	19082.17	742.63	4317.80	281.36	19.18	901.94	21.50	364.28	32.91	48.00	398.47
65	Auger	17122.79	1571.36	2.52	12.45	34.76	12.03	23551.37	899.02	7371.80	544.93	29.45	593.09	14.08	877.65	38.93	86.53	201.85
66	Auger	16896.00	2123.16	1.97	8.01	33.86	10.35	16568.35	833.65	4932.90	358.28	24.03	908.96	15.20	497.77	46.33	70.24	368.85
67	Excavated	14200.37	1994.56	2.16	7.88	30.03	9.88	16880.42	829.08	4322.50	299.06	20.47	906.96	17.56	393.74	39.63	55.81	387.38
68	Excavated	23115.43	1067.56	2.54	11.62	44.17	12.25	24044.10	2137.10	7859.00	394.95	33.86	541.90	6.44	703.64	44.54	109.31	92.68
69	Excavated	15515.76	1089.16	1.56	5.26	30.21	7.45	12475.71	862.24	3418.00	97.59	15.66	543.77	16.21	365.32	24.45	56.76	378.89
70	Auger	16514.90	2059.06	2.00	7.76	33.75	10.84	16844.91	782.34	4341.30	272.82	19.60	954.13	29.27	408.35	52.48	58.67	456.70
70R	Auger	17125.86	2037.06	2.07	7.57	35.19	11.14	16981.64	888.94	4314.10	308.98	20.22	952.86	32.54	437.12	66.12	68.97	461.82
71	Auger	17080.53	1518.16	2.11	9.55	35.53	11.23	19931.21	920.22	5292.20	303.92	25.89	710.29	17.59	493.51	38.76	57.31	366.93
72	Auger	21320.88	1526.96	1.94	8.89	35.29	10.20	15684.32	857.23	5374.00	318.20	21.25	781.14	15.72	429.92	43.60	63.48	368.16
73	Excavated	16310.28	1283.66	2.11	8.82	32.12	10.86	18717.59	811.09	4446.40	340.18	21.45	647.23	12.28	387.86	33.42	43.37	281.75
74	Auger	16161.28	981.56	2.42	10.34	34.56	10.28	24818.87	837.49	5054.90	314.65	26.89	494.06	11.31	672.39	35.84	65.16	218.88
75	Auger	17409.28	1721.96	2.34	9.82	37.14	11.10	20011.94	885.57	6726.50	333.00	25.72	622.81	15.76	755.29	43.03	98.64	313.35
76	Excavated	17483.26	774.99	2.07	9.52	32.53	11.58	18382.14	827.15	5152.90	234.46	29.82	415.49	14.89	638.81	40.82	56.49	254.91
77	Auger	17963.12	1687.76	2.50	10.03	36.44	11.26	22338.20	1088.60	5897.90	344.14	26.87	588.15	16.31	653.53	173.92	77.45	368.94
78	Excavated	17269.97	1161.86	2.09	7.57	34.48	6.72	19121.39	1173.30	4473.30	188.90	18.60	505.03	15.33	434.49	33.08	59.71	305.49

Case Study 1: Soil Analyses (Experiment 3), p.p.m. of Element (cont)

Sample No	Source	Al	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Ni	P	Pb	Ti	Zn	Na	S
79	Auger	16927.69	1331.76	2.26	10.05	35.20	10.10	20579.79	832.32	4944.80	356.08	23.44	622.48	14.00	596.93	44.73	96.10	310.20
80	Auger	16601.31	2003.76	2.04	8.69	34.71	10.97	18354.45	906.72	4830.00	360.79	22.84	952.25	22.52	461.04	46.70	82.76	417.18
80R	Auger	17043.24	1929.76	2.24	9.25	35.66	10.99	19753.06	953.15	5060.90	469.44	25.13	928.56	21.47	456.87	61.02	68.33	393.28
81	Auger	18166.37	1967.46	2.67	10.24	38.64	8.94	25087.89	1100.60	5452.90	503.99	23.83	698.00	17.64	526.11	43.87	90.46	395.32
82	Excavated	15729.87	2369.36	2.15	7.59	36.50	10.37	19287.12	786.10	4372.60	295.77	22.02	831.01	27.92	389.58	41.22	53.38	449.82
83	Auger	17292.65	1719.16	2.13	8.86	35.39	9.58	20151.21	915.33	5188.70	327.36	24.06	723.72	17.45	498.27	44.12	93.58	426.65
84	Auger	18675.60	1764.26	2.54	9.72	39.86	9.54	23166.63	1096.60	5856.00	435.09	26.27	637.51	17.50	603.81	44.63	77.11	366.94
85	Auger	16010.91	1573.36	1.83	6.93	33.98	9.82	16486.69	769.22	4339.70	305.88	20.10	848.33	19.66	388.73	45.27	55.86	387.41
86	Auger	16877.47	1103.56	2.52	11.68	35.21	8.69	23775.84	956.91	6108.20	447.86	29.67	459.93	12.13	750.64	52.50	80.45	191.95
87	Excavated	18655.35	935.22	2.13	9.83	36.49	18.58	20317.12	1420.10	6874.30	384.10	28.03	425.46	7.52	557.78	45.83	66.60	79.45
88	Auger	23228.30	1904.26	3.31	15.27	45.35	15.70	31461.42	1652.70	10223.22	603.55	39.39	468.39	10.51	833.43	53.90	132.65	87.88
89	Auger	16764.36	1086.96	2.21	7.75	34.26	7.98	19912.64	890.69	4409.00	244.82	25.43	474.01	8.94	647.25	39.34	59.42	279.88
90	Excavated	17228.25	1220.36	2.42	10.31	34.97	9.31	20483.34	915.47	5670.90	413.32	25.20	444.96	21.57	666.35	61.08	82.52	242.66
90R	Excavated	17621.63	1084.16	2.19	9.46	38.39	8.61	19687.39	1001.80	5592.80	321.47	24.73	414.48	19.02	558.09	47.42	65.02	233.63
91	Auger	15930.04	1806.96	2.44	11.36	36.56	10.19	23039.23	1178.70	6482.90	476.86	27.66	525.55	8.06	848.61	38.95	107.47	181.41
92	Excavated	15755.56	2295.56	2.32	9.30	32.91	13.15	20036.06	855.18	4890.50	450.42	21.21	951.30	26.89	525.29	55.36	66.64	407.57
93	Auger	17326.88	1518.56	2.10	8.44	36.25	13.76	18479.16	968.55	4911.60	339.44	22.84	677.43	21.43	443.88	40.45	91.77	361.77
94	Auger	18589.92	1861.16	2.22	7.53	36.84	10.10	18235.38	930.67	4378.40	221.76	22.59	916.53	23.30	397.89	45.71	71.83	553.71
94R	Auger	17531.96	1754.46	2.14	7.19	36.51	9.84	18895.50	870.59	4111.50	234.47	21.19	876.49	22.20	407.45	49.61	63.62	524.37
97	Auger	15650.12	923.20	2.40	13.97	37.13	11.34	25271.41	1043.70	6324.30	634.11	31.80	443.77	8.21	806.42	42.02	108.42	115.81

Case Study 2: Soil Analyses (Experiment 2), p.p.m. of Element

Sample No	Al	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Ni	P	Pb	Ti	Zn	Na	S
1	19996.43	3187.36	2.83	12.21	50.89	17.91	24519.91	1300.80	8324.30	527.53	35.83	1144.20	28.72	595.97	72.05	197.31	467.58
2	19296.68	3352.86	2.53	11.53	49.61	17.38	24566.77	1140.40	7905.30	516.99	34.67	1241.90	30.61	569.79	74.06	151.98	488.69
3	21384.94	3637.26	3.17	13.53	60.05	24.22	28023.81	1391.40	9889.60	615.21	45.11	1379.60	37.92	759.06	95.82	219.19	525.92
4	19456.97	3114.16	3.08	13.94	51.63	21.93	26599.93	1552.00	8578.80	762.07	38.83	1365.70	40.15	623.19	90.27	159.01	488.90
5	19503.59	2508.26	2.88	12.98	52.73	22.69	27250.95	1348.40	8056.30	679.84	39.21	1110.60	39.86	527.47	83.61	121.80	401.92
6	18616.30	2512.96	2.95	12.52	48.09	23.71	27469.13	1244.20	7739.50	603.97	38.13	1102.30	27.57	540.57	74.40	113.45	344.96
7	21341.52	4215.26	2.99	15.55	58.47	22.03	29305.71	1453.80	10609.11	694.31	45.26	1130.80	39.06	767.72	84.11	225.13	408.33
8	17945.73	2778.46	2.68	12.66	48.77	18.45	25298.97	1098.50	7876.60	626.82	38.51	1182.80	30.29	524.24	65.06	123.43	421.24
9	22547.94	4006.36	3.54	17.48	60.96	24.08	33622.60	1517.50	11724.61	718.56	51.59	1034.80	42.19	878.56	84.13	283.72	329.90
10	20446.46	2551.76	2.72	12.65	52.19	17.22	27986.29	1223.60	8393.00	510.54	37.70	1080.70	32.02	608.70	80.20	180.48	425.45
10R	20509.93	2598.16	2.68	11.66	49.76	17.85	23117.62	1227.20	7921.90	488.99	35.35	1131.30	30.85	557.81	71.16	151.89	461.53
11	21602.96	3826.26	2.83	12.10	53.40	19.21	25363.76	1184.70	8542.80	520.12	36.43	1278.90	40.31	662.52	84.58	193.64	461.86
12	21312.72	3890.16	3.01	14.04	58.61	22.23	27866.05	1483.20	10164.33	649.80	42.07	1287.20	40.59	852.53	83.19	222.36	449.55
13	19615.37	3034.16	2.95	13.97	53.43	31.60	27049.24	1404.10	8280.20	729.51	38.96	1454.90	43.06	565.80	86.75	139.59	488.69
14	20702.12	3280.96	2.73	11.98	53.65	19.15	23017.69	1225.30	8374.90	478.47	36.91	1218.50	39.38	631.00	79.51	161.37	478.34
15	19093.15	3329.66	3.11	14.00	56.20	24.07	27670.39	1264.20	8955.10	617.60	45.21	1260.00	38.22	654.77	75.24	165.82	495.83
16	20122.68	3435.76	3.06	15.39	55.31	23.25	29082.78	1375.20	10716.81	744.33	46.14	1666.10	35.84	716.28	92.99	179.02	584.23
17	19887.19	2831.96	2.73	12.77	52.19	21.63	25861.46	1203.00	8351.90	628.68	38.99	1187.20	33.18	536.36	77.32	134.10	449.13
18	18244.24	2414.26	2.85	14.13	46.26	19.77	29671.61	1427.50	8715.20	581.15	42.59	866.29	19.43	581.24	60.96	93.57	235.96
19	19852.44	2857.86	2.91	13.98	52.59	22.50	27726.45	1344.40	8538.40	717.15	41.23	1255.40	42.74	563.23	83.47	142.36	456.27

Case Study 2: Soil Analyses (Experiment 2), p.p.m. of Element (cont)

Sample No	Al	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Ni	P	Pb	Ti	Zn	Na	S
20	19319.03	4205.76	2.99	15.55	58.53	25.72	28710.75	1328.80	9318.80	770.23	47.40	1497.90	34.13	700.14	82.41	163.10	605.59
20R	19343.27	4157.56	3.20	15.10	57.46	26.11	31163.49	1356.70	9161.40	804.58	44.89	1615.00	39.40	741.29	83.43	171.13	648.59

Case Study 3: Soil Analyses, p.p.m. of Element

Sample No	Al	Ca	Cd	Co	Cu	Fe	K	Mg	Mn	Ni	P	Pb	Ti	Zn	Na	S
21	33873.13	5500.36	2.65	8.85	14.67	14718.12	1202.40	6701.00	102.72	24.47	550.37	12.37	153.85	44.46	131.39	599.98
22	30591.35	6507.86	2.29	7.71	14.02	11777.09	1115.70	5670.40	81.71	22.95	533.44	9.21	137.90	41.69	91.42	1043.39
23	29404.22	8503.56	2.44	9.66	26.57	13714.50	1283.80	6604.30	92.41	28.58	695.24	15.25	132.00	100.99	101.20	1671.19
24	26807.78	4813.96	2.56	11.48	12.21	20686.62	1683.20	7490.20	119.77	31.70	434.31	14.64	312.51	59.86	121.80	157.93
25	38363.87	9859.66	3.16	8.60	70.24	15251.11	1244.60	5914.50	161.19	31.40	660.34	15.27	117.00	37.52	95.79	1528.09
26	33828.81	5721.66	2.92	9.15	13.79	15537.94	1321.20	7030.00	108.75	24.92	546.94	16.00	161.82	51.67	115.39	688.78
27	28833.20	4374.56	3.30	13.02	10.42	27691.66	1446.50	7389.70	239.77	30.24	679.44	24.77	254.07	57.27	133.39	292.17
28	53609.81	10668.92	4.48	11.64	25.18	22004.10	1692.60	6455.60	128.81	35.76	499.84	7.34	125.45	60.69	124.25	1157.59
29	29529.71	4826.96	3.06	12.35	12.49	26274.77	1480.30	7166.70	199.26	30.19	754.87	25.03	258.31	59.81	140.35	381.48
30	24747.70	4351.96	2.71	12.29	13.38	22747.00	1985.50	8340.60	146.25	33.40	363.52	8.10	322.19	47.27	123.30	91.36
30R	24779.95	4391.86	2.59	12.92	13.15	22765.27	1953.00	8345.70	148.01	33.11	372.92	8.65	333.05	47.86	121.98	89.98
31	31472.96	8302.96	2.76	11.13	18.88	16697.06	1221.40	6625.90	154.18	27.75	726.23	15.61	176.95	72.03	97.24	1397.29

Case Study 3: Soil Analyses, p.p.m. of Element (cont)

Sample No	Al	Ca	Cd	Co	Cu	Fe	K	Mg	Mn	Ni	P	Pb	Ti	Zn	Na	S
32	33026.90	9084.16	3.05	9.08	90.21	16334.66	1235.90	6363.80	145.35	30.83	556.73	11.95	182.94	37.44	107.84	1311.29
33	35444.75	5782.66	2.95	9.12	32.04	18308.01	1204.60	6260.50	131.24	26.60	698.88	20.15	155.49	45.19	111.34	759.38
34	32893.67	4290.86	2.57	7.92	6.52	18964.48	1055.50	5797.90	90.65	22.19	660.11	24.90	198.96	51.85	134.26	345.73
35	34156.41	6100.66	2.54	8.29	13.56	12055.54	1317.90	6969.00	79.91	23.94	485.16	11.86	191.42	49.77	130.35	755.51
36	35328.01	5585.56	2.70	8.97	14.37	13549.12	1446.90	7193.70	91.14	24.54	519.51	12.18	223.61	46.95	115.25	611.56
37	29186.92	5021.36	2.66	11.49	14.88	19506.68	1627.20	7131.00	169.49	28.55	765.09	20.19	249.58	60.92	127.16	741.53
38	25550.11	5581.86	2.26	10.25	12.97	15555.68	1303.10	6463.90	141.92	27.23	596.94	13.05	222.91	55.98	129.21	1031.89
39	34630.93	6756.06	2.81	9.65	9.29	16857.91	1045.90	5183.50	81.51	31.51	573.46	14.06	183.83	34.81	124.44	1022.89
40	31824.90	4732.96	3.47	14.26	8.45	32161.60	1604.10	7152.20	152.94	33.08	509.67	16.82	237.30	49.62	148.13	285.54
40R	34055.86	5069.16	3.36	13.99	8.93	31979.68	1601.90	7354.30	141.32	35.34	491.02	15.84	218.07	50.68	157.81	298.76

Appendix 3: ICP-MS Analysis of Plant Samples

Experiment 2: Plant Analyses, p.p.m. of Element

Sample	Sample Co- ordinate	Feature	Al	Ca	Cr	Cu	Fe	K	Mg	Mn	Pb	Zn	Na	S
156	60; 10	Interior	99.69	4218.71	0.30	4.17	104.50	38071.80	2138.70	67.58	5056.30	2237.19	9.71	26.69
157	10; 10	Inter-ditch	128.82	5298.11	0.27	4.18	122.64	40346.45	2600.50	30.34	4804.30	2591.79	12.26	19.69
158	00; 15	Inter-ditch	82.60	5237.91	0.36	5.11	96.12	45681.15	2622.10	31.28	5893.40	2551.69	6.59	25.57
159	30; 20	Interior	204.49	4955.61	0.48	5.19	174.34	40406.11	2335.90	50.92	5018.00	2602.69	19.93	23.01
160	00; 10	Outer ditch reverse anomaly/ bank	93.75	4305.21	0.27	4.27	87.40	37158.02	2010.40	51.00	4317.90	2278.89	6.88	22.92
161	20; 00	Inter-ditch	169.68	5013.71	0.66	4.59	135.21	43784.47	2110.60	50.92	4710.90	2506.19	9.34	28.71
162	30; 10	Interior ditch branch	95.55	4507.51	0.86	5.07	89.63	41678.67	2210.80	51.77	4722.80	2430.89	5.00	25.96
163	20; 10	Inter-ditch	47.53	4258.81	0.55	4.47	63.79	40140.77	2074.10	43.16	4234.50	2426.69	2.98	22.75
163R	20; 10	Inter-ditch	48.95	4290.61	0.47	4.31	62.21	40188.19	2097.80	42.24	4142.30	2404.59	2.68	19.74
164	50; 20	Interior	132.43	5000.01	0.73	4.44	130.94	40096.79	2593.00	54.51	4725.30	2339.49	9.65	35.76
165	50; 10	Interior	87.33	5188.41	1.26	5.12	102.52	34117.99	2584.20	77.41	4466.70	2433.79	6.36	38.32
166	60; 00	Internal ditch	439.73	5731.71	1.67	6.90	399.28	38430.78	2698.80	57.65	4811.70	2395.59	32.34	25.38
167	20; 20	Internal ditch	256.56	4594.91	0.96	5.31	224.54	40371.80	2344.30	53.66	4674.90	2550.99	18.68	32.31
168	30; 00	Inter-ditch	68.83	4032.11	0.71	4.18	69.89	35336.12	1808.80	63.17	4414.90	2106.49	4.78	23.62
169	00; 20	Inter-ditch	195.58	4492.31	0.92	3.77	160.06	39548.02	2269.90	27.36	4494.10	2451.29	16.13	18.61
170	40; 00	Internal ditch	115.00	4602.81	0.61	4.11	123.53	40276.57	2284.70	29.12	5141.10	2199.49	9.37	29.77
171	60; 20	Interior	207.82	3903.21	1.02	4.11	177.93	38946.39	2028.30	44.88	4390.60	2193.39	15.33	29.22
171R	60; 20	Interior	197.62	3784.91	0.81	4.08	172.61	38458.90	2003.60	44.14	4313.00	2150.29	14.47	18.28
181	40; 20	Interior	115.84	4576.41	0.42	4.32	108.86	37095.96	2368.80	21.21	4571.10	2236.59	7.31	34.36
182	50; 00	Internal ditch	114.32	4703.01	0.36	4.50	126.37	36678.41	2457.00	53.04	4493.40	2270.39	6.48	25.11

Experiment 2: Plant Analyses, p.p.m. of Element (cont)

Sample	Sample Co- ordinate	Feature	Al	Ca	Cr	Cu	Fe	K	Mg	Mn	Pb	Zn	Na	S
183	40; 10	Interior	200.23	5146.61	0.55	4.60	166.23	38563.75	2379.20	27.86	5119.30	2282.59	13.18	36.67
184	00; 00	Enclosure exterior	149.33	4283.61	0.67	4.50	127.36	36784.60	2122.70	56.56	4334.30	2317.59	10.18	20.09
185	00; 05	Outer ditch	149.70	4904.81	0.56	4.08	119.80	33235.90	2431.00	17.63	4042.30	2136.59	12.04	17.93
185R	00; 05	Outer ditch	121.99	4742.01	0.53	4.09	103.70	32650.86	2347.30	17.01	3969.00	2072.29	10.07	23.62

Experiment 3: Plant Analyses, p.p.m. of Element

Sample	Context and Treatment Letter	Watering Regime	Al	Ca	Cr	Cu	Fe	K	Mg	Mn	Pb	Zn	Na	S
99	1005O	Optimum	879.65	3149.71	1.90	5.03	652.04	26564.39	2440.90	42.24	2497.40	2491.59	50.60	16.21
100	1006W	Waterlogged	746.61	2775.41	1.86	4.12	535.27	22382.02	2050.40	19.43	1850.00	1589.59	55.41	12.00
101	1003W	Waterlogged	718.99	3229.81	2.74	5.61	403.94	25577.86	2220.00	19.10	2862.20	1853.49	55.34	14.33
102	1001D	Dry	329.92	4284.61	1.56	4.37	262.99	22191.67	3320.20	16.35	2110.30	2594.19	23.53	14.15
103	2003D	Dry	465.59	2515.51	1.28	3.96	366.42	27700.27	2216.70	19.74	1846.80	2404.59	35.53	11.75
104	3003D	Dry	698.84	2350.61	1.44	4.72	725.69	22464.02	2162.40	51.47	1379.10	2177.29	40.38	21.27
105	2001D	Dry	110.68	3205.81	1.11	2.36	105.10	26228.70	2503.70	23.04	2121.00	2732.59	9.18	16.86
106	1006D	Dry	399.08	2254.71	1.74	2.99	306.12	21047.52	1991.60	19.26	1161.00	2207.99	31.65	10.68
107	2005W	Waterlogged	576.77	3785.81	2.07	6.24	552.87	28393.84	2688.10	16.92	3175.30	1863.59	42.67	16.59
108	1001O	Optimum	209.32	3771.11	0.97	4.82	174.13	20687.88	2928.20	22.71	2428.40	2578.99	17.80	12.06
108R	1001O	Optimum	199.49	3629.21	0.82	4.59	167.97	20815.07	2830.20	12.27	2453.40	2533.79	16.76	12.60

Experiment 3: Plant Analyses, p.p.m. of Element (cont)

Sample	Context and treatment letter	Watering regime	Al	Ca	Cr	Cu	Fe	K	Mg	Mn	Pb	Zn	Na	S
109	1002W	Waterlogged	1372.78	3061.71	2.30	5.40	847.78	21372.31	2153.70	36.20	1823.30	1916.49	68.24	15.58
110	1005D	Dry	463.26	2553.11	1.67	3.82	336.13	20975.40	2064.40	30.37	1442.10	2385.89	32.19	8.92
111	1003O	Optimum	416.71	2693.31	1.01	4.94	234.99	28668.77	2110.70	19.44	2571.60	2256.09	32.40	12.47
112	2006O	Optimum	1534.68	1938.91	3.29	3.84	932.49	18274.50	1659.50	21.54	1379.40	1530.89	89.01	10.71
113	3003W	Waterlogged	597.49	2744.81	1.57	4.35	407.44	25482.82	2284.30	26.43	2419.90	1766.29	43.74	14.04
114	2005O	Optimum	365.08	3039.01	1.08	5.25	280.87	28517.56	2539.90	14.03	2683.20	2198.59	26.08	15.80
115	1002D	Dry	1734.78	3696.31	3.62	7.50	1159.41	25465.53	2637.50	41.87	2127.30	2598.79	87.02	19.20
116	2002D	Dry	570.32	2511.71	2.17	6.44	518.52	32088.99	1929.50	26.62	2003.80	2111.49	51.94	18.72
117	2006W	Waterlogged	7026.98	2079.71	15.05	8.26	4847.41	19620.87	2845.10	68.52	1660.70	1594.19	364.96	23.14
118	3002O	Optimum	441.84	2508.51	1.03	4.84	269.76	25559.23	2404.70	19.47	1892.00	2071.79	30.02	10.98
118R	3002O	Optimum	441.48	2657.71	0.77	4.97	273.12	25307.92	2499.80	19.87	1946.00	2117.79	29.92	9.51
119	3001W	Waterlogged	349.77	3901.01	2.02	4.93	273.31	28383.24	2601.50	16.21	4189.70	1723.19	27.57	21.80
120	3001O	Optimum	493.96	3373.91	1.43	5.39	522.06	25119.43	2670.80	14.07	2947.70	1942.09	37.44	21.45
121	2006D	Dry	1882.68	2176.91	4.13	4.73	1302.71	20077.45	2055.90	34.61	1393.20	1796.89	102.29	8.33
122	1002O	Optimum	454.36	2697.81	1.35	5.31	326.60	26404.60	2554.90	40.33	1699.80	3171.89	27.28	13.36
123	2001O	Optimum	140.43	3611.11	0.82	3.19	131.04	24412.79	2703.90	10.34	2673.90	2106.99	9.81	13.86
124	3002D	Dry	611.50	2326.71	1.84	4.26	425.08	19710.69	2251.40	20.18	1387.70	2113.69	46.56	13.28
125	2005D	Dry	318.58	2913.11	1.15	5.02	290.05	25477.77	2442.90	16.37	1995.80	2317.89	22.86	16.04
126	2002O	Optimum	1032.58	3030.41	3.41	6.62	885.98	32018.79	2356.40	30.49	3642.90	1637.49	86.70	9.39
127	2003D	Dry	256.68	2321.61	2.16	3.33	291.84	22336.97	1787.80	28.97	1330.50	2364.59	18.59	13.44
128	2003O	Optimum	443.83	2859.01	1.58	4.99	376.12	28155.80	2222.50	20.75	2541.10	2167.19	31.39	21.44

Experiment 3: Plant Analyses, p.p.m. of Element (cont)

Sample	Context and treatment letter	Watering regime	Al	Ca	Cr	Cu	Fe	K	Mg	Mn	Pb	Zn	Na	S
128R	2003O	Optimum	430.01	2883.31	2.31	4.90	381.25	28537.05	2220.70	20.78	2513.60	2163.19	31.29	19.11
129	2002W	Waterlogged	875.13	3550.71	2.49	7.61	691.65	30070.92	2462.70	29.31	3880.80	1683.19	67.43	16.35
130	2001W	Waterlogged	164.50	3398.21	0.89	3.07	131.18	20067.70	2345.90	13.63	2483.30	1426.99	12.11	14.13
131	1001W	Waterlogged	361.15	3446.11	1.70	4.59	312.44	20420.63	2391.90	11.27	2481.60	1718.49	30.36	32.47
132	3002W	Waterlogged	903.59	3005.01	2.40	4.69	519.61	22583.95	2390.60	21.85	1735.80	1709.99	55.43	12.27
133	1003D	Dry	312.84	2307.01	1.08	4.30	205.02	21405.17	2174.90	23.33	1811.60	2496.89	25.39	12.91
134	1005W	Waterlogged	1362.78	2890.41	3.10	6.44	1246.01	22680.44	2219.70	29.55	2345.80	1648.99	79.99	21.29
135	3001D	Dry	360.62	3200.51	2.51	3.37	321.05	25707.66	2813.40	21.35	2278.40	2545.19	30.87	15.97
136	2003W	Waterlogged	706.62	3006.01	2.13	5.06	555.64	27679.71	2138.60	29.11	2832.30	1973.99	48.56	17.92
137	1006O	Optimum	353.15	2875.11	0.79	4.53	260.85	23877.14	2173.30	15.37	1750.50	2109.89	25.63	11.30
138	3003O	Optimum	531.80	2641.91	1.63	4.15	389.38	26689.41	2383.70	27.31	1982.20	1914.99	39.31	14.98
138R	3003O	Optimum	529.02	2684.21	2.25	4.05	389.90	26039.25	2402.40	27.09	1936.10	1875.49	38.48	25.63

Experiment 4: Plant Analyses, p.p.m. of Element

Sample	Pot No	Treatment	Al	Ca	Cr	Cu	Fe	K	Mg	Mn	Pb	Zn	Na	S
172	W3	Dry to optimum	122.52	5525.91	0.83	15.52	193.08	52021.19	5370.00	116.04	10310.22	5133.29	6.30	45.43
173	W2	Wet to optimum	214.03	6505.91	1.24	8.74	392.15	27464.10	4837.00	183.29	6687.90	2387.09	9.62	25.97
174	W49	Wet to dry	169.44	5850.51	0.81	7.71	325.60	27839.57	4813.90	167.08	7059.40	2160.39	7.79	24.36
176	W9	Optimum constant	645.65	7148.81	3.69	10.92	429.24	41030.99	5195.70	213.83	6110.30	4640.19	21.84	54.61
177	W15	Dry to wet	81.13	5607.61	0.40	13.88	281.01	49150.20	4460.70	117.95	9532.40	3760.19	3.22	66.62

Experiment 4: Plant Analyses, p.p.m. of Element (cont)

Sample	Pot No	Treatment	Al	Ca	Cr	Cu	Fe	K	Mg	Mn	Pb	Zn	Na	S
178	W39	Dry constant	97.49	6471.11	0.65	10.99	413.72	58485.78	5305.20	116.87	7098.90	4112.89	4.92	56.15
179	W21	Optimum to dry	125.23	4842.61	0.60	8.63	247.94	42852.95	4023.70	102.24	5394.90	3882.19	5.60	39.20
180	W8	Optimum to wet	234.98	5943.31	1.10	11.13	2800.41	42152.42	4565.90	108.34	7550.60	3437.59	10.03	40.08
180R	W8	Optimum to wet	207.51	5449.01	1.29	10.65	2371.01	42292.39	4350.30	104.13	7183.30	3303.99	8.56	37.02

Experiment 5: Plant Analyses, p.p.m. of Element

Sample	Pot No	Treatment	Al	Ca	Cr	Cu	Fe	K	Mg	Mn	Pb	Zn	Na	S
139	D1	Deep; optimum	31.39	5964.91	0.18	10.09	76.49	46151.64	4478.90	115.41	7397.40	3232.69	1.50	43.05
140	D3	Shallow; dry	78.59	4962.61	0.52	9.18	163.02	61203.19	3622.90	89.89	5560.10	3397.59	5.08	45.60
141	D2	Shallow; wet	104.46	5507.31	0.51	7.03	114.73	43254.79	4018.60	124.07	6819.60	2400.19	3.76	18.80
142	D4	Medium; optimum	83.93	5427.41	0.50	11.18	110.53	65966.03	4378.20	106.98	8052.50	3460.69	4.52	42.32
143	D5	Medium; wet	35.12	4661.11	0.13	6.96	46.40	31940.21	3181.90	104.10	5286.00	1933.89	1.49	20.48
143R	D5	Medium; wet	25.51	4453.71	0.45	6.65	42.91	31679.03	3126.50	99.94	5258.60	1896.69	1.46	21.97
186	D9	Medium; dry	36.97	5901.91	0.06	8.21	64.98	48221.00	4360.40	125.36	5426.70	2744.89	1.80	44.94
187	D8	Deep; dry	85.81	4888.81	0.44	8.72	199.32	63475.65	3675.40	71.70	6542.10	2807.09	5.01	33.42
188	D7	Shallow; optimum	81.16	5495.21	0.38	10.95	115.86	48600.68	4080.90	106.05	7550.00	3690.49	4.24	42.57
189	D6	Deep; wet	136.59	5794.41	0.23	7.20	184.25	43636.30	3937.70	140.86	6494.20	2740.59	31.54	22.96
189R	D6	Deep; wet	113.64	5382.21	0.64	6.80	151.35	44785.66	3704.50	135.87	6359.70	2687.39	5.78	22.14

Appendix 4 Statistical Analysis of Variations in Soil Chemical Concentrations

Statistical Analysis of Soils Elemental Concentrations from The Three Case Studies

1: Case Study 1; 2: Case Study 3; 3: Case Study 2

Element	Case Study	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	22	20006.439	1146.881	244.515	19497.941	20514.938	17945.729	22547.944
	2	22	32360.952	6009.609	1281.252	29696.441	35025.464	24747.697	53609.808
	3	58	17226.843	1653.346	217.095	16792.117	17661.568	14200.371	23228.302
	Total	102	21090.583	6769.204	670.251	19760.985	22420.181	14200.371	53609.808
Ca	1	22	3260.330	597.892	127.471	2995.239	3525.420	2414.262	4215.262
	2	22	6174.073	1899.259	404.923	5331.989	7016.158	4290.862	10668.918
	3	58	1507.030	406.955	53.435	1400.027	1614.034	774.992	2369.362
	Total	102	2891.810	2096.481	207.582	2480.022	3303.598	774.992	10668.918
Cd	1	22	2.92659	.220586	.047029	2.82879	3.02439	2.526	3.536
	2	22	2.87564	.485606	.103531	2.66033	3.09094	2.261	4.475
	3	58	2.20309	.293732	.038569	2.12585	2.28032	1.558	3.309
	Total	102	2.50420	.478353	.047364	2.41024	2.59815	1.558	4.475
Co	1	22	13.62268	1.511557	.322265	12.95250	14.29287	11.531	17.475
	2	22	10.53818	1.999585	.426313	9.65162	11.42475	7.710	14.260
	3	58	9.61895	2.191892	.287810	9.04262	10.19528	5.255	15.596
	Total	102	10.68076	2.560251	.253503	10.17788	11.18365	5.255	17.475
Cr	1	22	53.67164	4.073868	.868552	51.86538	55.47789	46.263	60.956
	2	22	46.47686	8.335866	1.777213	42.78095	50.17278	36.827	70.851
	3	58	35.60945	3.357736	.440892	34.72658	36.49232	30.033	47.476
	Total	102	41.84917	9.040427	.895136	40.07346	43.62488	30.033	70.851
Cu	1	22	21.94127	3.473807	.740618	20.40107	23.48147	17.223	31.597
	2	22	20.73573	20.426255	4.354892	11.67923	29.79222	6.522	90.211
	3	58	10.67109	2.066997	.271410	10.12760	11.21458	6.387	18.575
	Total	102	15.27272	10.955299	1.084736	13.12089	17.42454	6.387	90.211
Fe	1	22	27315.697	2514.559	536.105	26200.804	28430.590	23017.685	33622.599
	2	22	19324.482	5935.977	1265.554	16692.617	21956.347	11777.087	32161.597
	3	58	20495.438	3559.003	467.320	19559.645	21431.230	12475.710	31461.421
	Total	102	21713.915	4972.004	492.301	20737.320	22690.509	11777.087	33622.599
K	1	22	1322.495	122.7162	26.1632	1268.086	1376.905	1098.5	1552.0
	2	22	1412.418	265.1893	56.5385	1294.840	1529.997	1045.9	1985.5
	3	58	983.242	256.7957	33.7189	915.721	1050.763	734.1	2137.1
	Total	102	1148.981	304.0040	30.1009	1089.269	1208.694	734.1	2137.1
Mg	1	22	8915.402	1069.405	227.997	8441.255	9389.550	7739.500	11724.613
	2	22	6800.199	785.803	167.533	6451.794	7148.605	5183.500	8345.700
	3	58	5409.034	1206.241	158.387	5091.869	5726.200	3418.000	10223.224
	Total	102	6465.365	1777.648	176.013	6116.202	6814.528	3418.000	11724.613

1: Case Study 1; 2: Case Study 3; 3: Case Study 2 (cont)

Element	Case Study	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Mn	1	22	635.750	99.568	21.228	591.604	679.896	478.473	804.583
	2	22	132.197	40.5006	8.6347	114.240	150.154	79.914	239.773
	3	58	359.185	128.754	16.906	325.331	393.039	97.592	694.723
	Total	102	369.878	198.812	19.685	330.828	408.929	79.914	804.583
Ni	1	22	40.95455	4.520366	.963745	38.95033	42.95876	34.670	51.590
	2	22	29.01127	4.029519	.859096	27.22468	30.79786	22.189	35.761
	3	58	24.64157	4.641810	.609500	23.42107	25.86207	15.662	39.385
	Total	102	29.10254	7.862034	.778457	27.55829	30.64679	15.662	51.590
P	1	22	1249.640	189.5853	40.4197	1165.583	1333.698	866.3	1666.1
	2	22	576.092	116.2883	24.7928	524.533	627.652	363.5	765.1
	3	58	654.712	195.1195	25.6204	603.408	706.016	158.4	965.7
	Total	102	766.073	312.5524	30.9473	704.682	827.464	158.4	1666.1
Pb	1	22	35.70482	6.010637	1.281472	33.03985	38.36979	19.427	43.062
	2	22	15.14618	5.218067	1.112496	12.83262	17.45974	7.337	25.025
	3	58	16.34950	6.123925	.804111	14.73930	17.95970	4.307	32.536
	Total	102	20.26464	10.038692	.993979	18.29285	22.23642	4.307	43.062
Ti	1	22	643.555	104.475	22.274	597.233	689.877	524.239	878.559
	2	22	206.781	63.062	13.445	178.820	234.741	116.999	333.049
	3	58	559.137	159.012	20.879	517.327	600.947	364.279	1114.429
	Total	102	501.346	206.371	20.433	460.811	541.882	116.999	1114.429
Zn	1	22	80.21427	8.453501	1.802293	76.46620	83.96235	60.960	95.822
	2	22	52.92318	13.985895	2.981803	46.72218	59.12418	34.810	100.985
	3	58	45.18210	18.761291	2.463478	40.24907	50.11513	24.452	173.915
	Total	102	54.40771	21.180065	2.097139	50.24755	58.56787	24.452	173.915
Na	1	22	167.88509	43.618187	9.299429	148.54587	187.22431	93.571	283.721
	2	22	121.96873	16.764925	3.574294	114.53558	129.40188	91.421	157.811
	3	58	75.97290	18.777020	2.465543	71.03573	80.91006	43.374	132.651
	Total	102	105.71776	45.391990	4.494477	96.80193	114.63360	43.374	283.721
S	1	22	459.929	89.984	19.184	420.032	499.825	235.959	648.589
	2	22	739.240	477.365	101.774	527.588	950.891	89.975	1671.189
	3	58	312.593	125.809	16.519	279.513	345.673	70.660	562.219
	Total	102	436.393	294.781	29.187	378.493	494.294	70.660	1671.189

*Statistical Analysis of Variance of Mean Concentrations from the 3 Case studies;
Significance level 0.005*

Element		Sum of Squares	df	Mean Square	F	Sig.
Al	Between Groups	3686177319.734	2	1843088659.867	193.730	.000
	Within Groups	941858173.439	99	9513718.924		
	Total	4628035493.173	101			
Ca	Between Groups	351220909.978	2	175610454.989	187.550	.000
	Within Groups	92697830.583	99	936341.723		
	Total	443918740.561	101			
Cd	Between Groups	12.219	2	6.110	55.533	.000
	Within Groups	10.892	99	.110		
	Total	23.111	101			
Co	Between Groups	256.247	2	128.123	31.258	.000
	Within Groups	405.796	99	4.099		
	Total	662.043	101			
Cr	Between Groups	5804.277	2	2902.139	117.252	.000
	Within Groups	2450.385	99	24.751		
	Total	8254.662	101			
Cu	Between Groups	2863.061	2	1431.530	15.307	.000
	Within Groups	9258.815	99	93.523		
	Total	12121.876	101			
Fe	Between Groups	902077494.222	2	451038747.111	28.000	.000
	Within Groups	1594726700.535	99	16108350.510		
	Total	2496804194.757	101			
K	Between Groups	3782375.877	2	1891187.938	33.723	.000
	Within Groups	5551885.141	99	56079.648		
	Total	9334261.017	101			
Mg	Between Groups	199243945.603	2	99621972.801	82.243	.000
	Within Groups	119919536.655	99	1211308.451		
	Total	319163482.258	101			
Mn	Between Groups	2804596.539	2	1402298.270	116.900	.000
	Within Groups	1187570.221	99	11995.659		
	Total	3992166.760	101			
Ni	Between Groups	4244.739	2	2122.370	105.150	.000
	Within Groups	1998.231	99	20.184		
	Total	6242.970	101			
P	Between Groups	6657731.966	2	3328865.983	102.702	.000
	Within Groups	3208858.891	99	32412.716		
	Total	9866590.857	101			
Pb	Between Groups	6710.192	2	3355.096	95.774	.000
	Within Groups	3468.116	99	35.031		
	Total	10178.308	101			
Ti	Between Groups	2547533.939	2	1273766.969	71.895	.000
	Within Groups	1753984.306	99	17717.013		
	Total	4301518.245	101			

Statistical Analysis of Variance of Mean Concentrations from the Three Case Studies; Significance Level 0.005 (cont)

Element		Sum of Squares	df	Mean Square	F	Sig.
Zn	Between Groups	19636.500	2	9818.250	37.863	.000
	Within Groups	25671.609	99	259.309		
	Total	45308.109	101			
Na	Between Groups	142151.062	2	71075.531	106.690	.000
	Within Groups	65952.646	99	666.188		
	Total	208103.708	101			
S	Between Groups	2918868.097	2	1459434.049	24.666	.000
	Within Groups	5857670.245	99	59168.386		
	Total	8776538.342	101			

Statistical Analysis of Elemental Concentrations in Soils from Archaeological Features at the Three Case Studies

1: Case Study 1; 2: Case Study 3; 3: Case Study 2

Element	Case Study	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	16	20107.663	1139.865	284.966	19500.271	20715.055	18244.239	22547.944
	2	17	32812.650	6444.424	1563.002	29499.232	36126.067	24747.697	53609.808
	3	43	17047.974	1398.983	213.342	16617.431	17478.518	14918.998	23228.302
	Total	76	21218.428	7135.869	818.540	19587.812	22849.044	14918.998	53609.808
Ca	1	16	3260.043	688.650	172.162	2893.087	3626.999	2414.262	4215.262
	2	17	6202.741	1856.392	450.241	5248.272	7157.210	4290.862	10668.918
	3	43	1506.842	364.448	55.577	1394.681	1619.003	774.992	2206.162
	Total	76	2926.336	2125.240	243.781	2440.697	3411.974	774.992	10668.918
Cd	1	16	2.95931	.206873	.051718	2.84908	3.06955	2.683	3.536
	2	17	2.87641	.513016	.124425	2.61264	3.14018	2.261	4.475
	3	43	2.22530	.315628	.048133	2.12817	2.32244	1.558	3.309
	Total	76	2.52547	.490123	.056221	2.41348	2.63747	1.558	4.475
Co	1	16	13.98675	1.542860	.385715	13.16462	14.80888	11.658	17.475
	2	17	10.51059	1.966290	.476895	9.49962	11.52156	7.924	14.260
	3	43	9.84626	2.348697	.358173	9.12343	10.56908	5.255	15.596
	Total	76	10.86654	2.663187	.305488	10.25798	11.47510	5.255	17.475
Cr	1	16	53.84988	4.104628	1.026157	51.66267	56.03708	46.263	60.956
	2	17	46.41535	8.585119	2.082197	42.00129	50.82941	36.827	70.851
	3	43	35.37493	3.405744	.519371	34.32680	36.42306	30.214	47.476
	Total	76	41.73396	9.222610	1.057906	39.62650	43.84142	30.214	70.851
Cu	1	16	22.59600	3.461979	.865495	20.75124	24.44076	17.223	31.597
	2	17	19.81241	19.372217	4.698453	9.85214	29.77269	6.522	90.211
	3	43	10.71356	1.693543	.258263	10.19236	11.23475	7.452	15.699
	Total	76	15.25039	10.587388	1.214457	12.83107	17.66982	6.522	90.211
Fe	1	16	27990.487	2407.728	601.932	26707.500	29273.475	23117.624	33622.599
	2	17	19026.904	5834.809	1415.149	16026.921	22026.886	12055.543	32161.597
	3	43	20849.446	3670.013	559.671	19719.983	21978.910	12475.710	31461.421
	Total	76	21945.149	5136.162	589.158	20771.486	23118.813	12055.543	33622.599
K	1	16	1354.64	114.982	28.745	1293.37	1415.91	1185	1552
	2	17	1417.82	282.958	68.627	1272.33	1563.30	1046	1986
	3	43	949.37	162.279	24.747	899.43	999.31	743	1653
	Total	76	1139.48	287.454	32.973	1073.79	1205.16	743	1986
Mg	1	16	9050.816	1155.600	288.900	8435.040	9666.592	7739.500	11724.613
	2	17	6821.935	788.208	191.168	6416.675	7227.194	5183.500	8345.700
	3	43	5436.926	1227.926	187.257	5059.026	5814.826	3418.000	10223.224
	Total	76	6507.549	1817.540	208.486	6092.224	6922.875	3418.000	11724.613

Element	Case Study	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Mn	1	16	662.742	98.370	24.592	610.324	715.160	488.993	804.583
	2	17	123.919	29.226	7.088	108.892	138.946	79.914	169.493
	3	43	375.949	135.158	20.611	334.354	417.545	97.592	694.723
	Total	76	379.952	210.417	24.136	331.869	428.034	79.914	804.583
Ni	1	16	41.5478	4.47168	1.11792	39.1650	43.9306	35.35	51.59
	2	17	28.9274	4.24460	1.02947	26.7450	31.1098	22.19	35.76
	3	43	25.0608	4.84336	.73861	23.5703	26.5514	15.66	39.39
	Total	76	29.3967	7.95653	.91268	27.5785	31.2148	15.66	51.59
P	1	16	1254.068	219.2212	54.8053	1137.253	1370.883	866.3	1666.1
	2	17	565.390	114.6664	27.8107	506.434	624.346	363.5	765.1
	3	43	663.103	172.0220	26.2331	610.162	716.044	415.5	965.7
	Total	76	765.660	308.2180	35.3550	695.229	836.091	363.5	1666.1
Pb	1	16	36.27331	6.453132	1.613283	32.83468	39.71194	19.427	43.062
	2	17	14.37106	4.580667	1.110975	12.01590	16.72622	7.337	24.902
	3	43	16.29991	5.485435	.836521	14.61174	17.98807	8.060	32.536
	Total	76	20.07338	10.058635	1.153805	17.77489	22.37188	7.337	43.062
Ti	1	16	651.462	113.329	28.332	591.073	711.850	527.469	878.559
	2	17	204.082	58.371	14.157	174.070	234.094	125.449	333.049
	3	43	567.200	149.655	22.822	521.142	613.257	364.279	877.649
	Total	76	503.715	207.738	23.829	456.245	551.186	125.449	878.559
Zn	1	16	81.43600	7.631796	1.907949	77.36930	85.50270	60.960	92.988
	2	17	53.42141	15.053065	3.650904	45.68184	61.16098	34.810	100.985
	3	43	45.86172	21.220025	3.236023	39.33116	52.39228	24.452	173.915
	Total	76	55.04203	22.576156	2.589663	49.88315	60.20090	24.452	173.915
Na	1	16	167.147	47.728	11.932	141.714	192.580	93.571	283.721
	2	17	123.562	15.354	3.724	115.667	131.456	97.241	157.811
	3	43	77.195	19.176	2.924	71.293	83.096	43.374	132.651
	Total	76	106.504	45.330	5.199	96.145	116.862	43.374	283.721
S	1	16	452.552	103.539	25.884	397.380	507.724	235.959	648.589
	2	17	756.483	460.963	111.800	519.478	993.489	89.975	1671.189
	3	43	314.844	107.853	16.447	281.652	348.036	87.881	562.219
	Total	76	442.623	292.744	33.580	375.728	509.518	87.881	1671.189

Statistical Analysis Variance in Soils from Archaeological Features at the Three Case Studies. Significance level = 0.005

<i>Element</i>		<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
Al	Between Groups	3052867725.888	2	1526433862.944	145.435	.000
	Within Groups	766179546.588	73	10495610.227		
	Total	3819047272.477	75			
Ca	Between Groups	270917292.074	2	135458646.037	145.781	.000
	Within Groups	67831274.270	73	929195.538		
	Total	338748566.344	75			
Cd	Between Groups	8.980	2	4.490	36.268	.000
	Within Groups	9.037	73	.124		
	Total	18.017	75			
Co	Between Groups	202.687	2	101.344	22.469	.000
	Within Groups	329.255	73	4.510		
	Total	531.942	75			
Cr	Between Groups	4460.091	2	2230.045	84.826	.000
	Within Groups	1919.150	73	26.290		
	Total	6379.241	75			
Cu	Between Groups	2102.195	2	1051.097	12.170	.000
	Within Groups	6304.763	73	86.367		
	Total	8406.958	75			
Fe	Between Groups	781136818.270	2	390568409.135	23.812	.000
	Within Groups	1197375467.213	73	16402403.660		
	Total	1978512285.483	75			
K	Between Groups	3611831.117	2	1805915.559	50.991	.000
	Within Groups	2585394.987	73	35416.370		
	Total	6197226.104	75			
Mg	Between Groups	154459654.313	2	77229827.156	60.427	.000
	Within Groups	93299314.769	73	1278072.805		
	Total	247758969.082	75			
Mn	Between Groups	2394608.661	2	1197304.331	94.381	.000
	Within Groups	926066.586	73	12685.844		
	Total	3320675.247	75			
Ni	Between Groups	3174.524	2	1587.262	73.641	.000
	Within Groups	1573.448	73	21.554		
	Total	4747.972	75			
P	Between Groups	4950788.324	2	2475394.162	83.117	.000
	Within Groups	2174088.497	73	29782.034		
	Total	7124876.820	75			
Pb	Between Groups	5364.066	2	2682.033	88.029	.000
	Within Groups	2224.144	73	30.468		
	Total	7588.210	75			
Ti	Between Groups	2048826.637	2	1024413.318	62.957	.000
	Within Groups	1187835.211	73	16271.715		
	Total	3236661.847	75			

Statistical Analysis Variance in Soils from Archaeological Features at the Three Case Studies. Significance level = 0.005 (cont)

Element		Sum of Squares	df	Mean Square	F	Sig.
Zn	Between Groups	14814.873	2	7407.436	23.097	.000
	Within Groups	23411.338	73	320.703		
	Total	38226.211	75			
Na	Between Groups	100727.308	2	50363.654	68.864	.000
	Within Groups	53388.680	73	731.352		
	Total	154115.988	75			
S	Between Groups	2378301.068	2	1189150.534	21.439	.000
	Within Groups	4049158.060	73	55467.919		
	Total	6427459.128	75			

Statistical Analysis of Soils from all Case Studies Grouped by Archaeological Feature

1: Ditch; 2: Bank; 3: Layer/fill; 4: Interior

Element	Feature	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	28	19255.637	3735.027	705.853	17807.345	20703.930	15515.756	31472.962
	2	20	16861.968	1698.054	379.696	16067.254	17656.682	14918.998	23228.302
	3	16	32133.051	7692.962	1923.240	28033.761	36232.342	17190.963	53609.808
	4	12	18506.211	1282.485	370.221	17691.358	19321.063	16757.940	20122.682
	Total	76	21218.428	7135.869	818.540	19587.812	22849.044	14918.998	53609.808
Ca	1	28	2544.080	1907.200	360.427	1804.545	3283.616	774.992	8503.562
	2	20	1529.594	403.494	90.224	1340.752	1718.435	923.202	2123.162
	3	16	5604.578	2104.505	526.126	4483.166	6725.989	1033.162	10668.918
	4	12	2575.178	1029.312	297.136	1921.184	3229.172	1277.762	4205.762
	Total	76	2926.336	2125.240	243.781	2440.697	3411.974	774.992	10668.918
Co	1	28	10.61432	2.894234	.546959	9.49205	11.73659	5.255	17.475
	2	20	10.58205	2.559815	.572392	9.38402	11.78008	6.932	15.272
	3	16	10.35675	2.122948	.530737	9.22551	11.48799	7.823	14.260
	4	12	12.60892	2.516885	.726562	11.00976	14.20807	8.757	15.552
	Total	76	10.86654	2.663187	.305488	10.25798	11.47510	5.255	17.475
Cr	1	28	41.38171	9.516195	1.798392	37.69172	45.07171	30.214	60.956
	2	20	35.26765	3.298239	.737509	33.72403	36.81127	30.553	45.352
	3	16	46.39038	9.242365	2.310591	41.46547	51.31528	32.419	70.851
	4	12	47.12450	9.099543	2.626812	41.34293	52.90607	34.919	58.532
	Total	76	41.73396	9.222610	1.057906	39.62650	43.84142	30.214	70.851
Cu	1	28	14.70557	6.353813	1.200758	12.24182	17.16932	7.452	31.597
	2	20	10.68840	1.476892	.330243	9.99719	11.37961	8.688	15.699
	3	16	18.70006	20.135427	5.033857	7.97065	29.42947	6.522	90.211
	4	12	19.52542	5.718455	1.650776	15.89208	23.15875	11.055	26.113
	Total	76	15.25039	10.587388	1.214457	12.83107	17.66972	6.522	90.211

Fe	1	28	21925.762	5065.143	957.222	19961.704	23889.819	12475.710	33622.599
	2	20	21706.812	3972.592	888.298	19847.582	23566.043	16486.690	31461.421
	3	16	19414.417	5835.220	1458.805	16305.048	22523.787	12055.543	32161.597
	4	12	25761.924	4229.550	1220.966	23074.596	28449.252	18525.647	31163.494
	Total	76	21945.149	5136.162	589.158	20771.486	23118.813	12055.543	33622.599
K	1	28	1061.08	238.320	45.038	968.67	1153.50	743	1518
	2	20	984.02	191.832	42.895	894.24	1073.80	769	1653
	3	16	1416.31	300.024	75.006	1256.43	1576.18	1046	1986
	4	12	1212.38	246.606	71.189	1055.69	1369.07	879	1552
	Total	76	1139.48	287.454	32.973	1073.79	1205.16	743	1986
Mg	1	28	6535.798	2174.569	410.955	5692.588	7379.008	3418.000	11724.613
	2	20	5666.201	1278.936	285.978	5067.640	6264.761	4314.100	10223.224
	3	16	6688.925	1033.841	258.460	6138.029	7239.820	4280.100	8345.700
	4	12	7602.050	1997.522	576.635	6332.885	8871.216	4537.200	10716.811
	Total	76	6507.549	1817.540	208.486	6092.224	6922.875	3418.000	11724.613
Mn	1	28	403.344	191.953	36.275	328.912	477.775	92.408	729.513
	2	20	423.723	128.507	28.735	363.580	483.866	216.973	651.013
	3	16	125.979	29.092	7.273	110.476	141.481	79.914	169.493
	4	12	591.048	185.606	53.579	473.120	708.977	303.923	804.583
	Total	76	379.952	210.417	24.136	331.869	428.034	79.914	804.583
Ni	1	28	29.2370	8.91718	1.68519	25.7793	32.6947	15.66	51.59
	2	20	26.2602	5.07859	1.13561	23.8833	28.6371	19.60	39.39
	3	16	28.5063	4.84552	1.21138	25.9243	31.0883	20.67	35.76
	4	12	36.1838	9.51491	2.74672	30.1383	42.2293	21.60	47.40
	Total	76	29.3967	7.95653	.91268	27.5785	31.2148	15.66	51.59
P	1	28	816.184	281.8748	53.2693	706.885	925.484	415.5	1454.9
	2	20	655.083	199.2912	44.5629	561.812	748.354	438.5	954.1
	3	16	540.766	106.0223	26.5056	484.271	597.262	363.5	765.1
	4	12	1131.923	346.5894	100.0517	911.710	1352.135	710.3	1666.1
	Total	76	765.660	308.2180	35.3550	695.229	836.091	363.5	1666.1
Pb	1	28	22.66586	10.377382	1.961141	18.64193	26.68979	8.940	43.062
	2	20	15.16720	6.920259	1.547417	11.92842	18.40598	8.060	32.536
	3	16	14.14750	4.723918	1.180980	11.63030	16.66470	7.337	24.902
	4	12	30.10242	9.522717	2.748972	24.05197	36.15286	17.590	42.743
	Total	76	20.07338	10.058635	1.153805	17.77489	22.37188	7.337	43.062
Tl	1	28	560.062	192.915	36.457	485.257	634.867	131.999	878.559
	2	20	606.643	147.854	33.061	537.445	675.841	388.729	848.609
	3	16	222.947	74.808	18.702	183.084	262.809	125.449	406.699
	4	12	575.053	99.713	28.784	511.698	638.408	443.949	741.289
	Total	76	503.715	207.738	23.829	456.245	551.186	125.449	878.559
Zn	1	28	60.00186	30.960706	5.851023	47.99655	72.00717	24.452	173.915
	2	20	45.27680	8.258059	1.846558	41.41191	49.14169	35.842	66.121
	3	16	48.44019	7.317505	1.829376	44.54096	52.33941	34.810	60.924
	4	12	68.54692	20.811099	6.007647	55.32418	81.76966	38.138	92.988
	Total	76	55.04203	22.576156	2.589663	49.88315	60.20090	24.452	173.915

Na	1	28	109.70389	60.835337	11.496798	86.11441	133.29337	43.374	283.721
	2	20	83.95930	19.013959	4.251651	75.06049	92.85811	55.858	132.651
	3	16	123.19000	19.257015	4.814254	112.92866	133.45134	68.925	157.811
	4	12	114.36442	48.720834	14.064493	83.40868	145.32016	54.690	179.021
	Total	76	106.50405	45.330782	5.199797	96.14553	116.86258	43.374	283.721
S	1	28	455.252	318.094	60.114	331.908	578.596	191.849	1671.189
	2	20	278.806	126.252	28.230	219.718	337.894	87.881	461.819
	3	16	628.856	376.701	94.175	428.126	829.586	89.975	1311.289
	4	12	437.874	123.469	35.642	359.425	516.322	235.959	648.589
	Total	76	442.623	292.744	33.580	375.728	509.518	87.881	1671.189

Statistical Analysis of Soils from all Case Studies Grouped by Archaeological Feature.
Significance level = 0.005

Element		Sum of Squares	df	Mean Square	F	Sig
Al	Between Groups	2481783722.087	3	827261240.696	44.541	.000
	Within Groups	1337263550.390	72	18573104.867		
	Total	3819047272.477	75			
Ca	Between Groups	159356515.643	3	53118838.548	21.320	.000
	Within Groups	179392050.701	72	2491556.260		
	Total	338748566.344	75			
Cd	Between Groups	3.465	3	1.155	5.716	.001
	Within Groups	14.551	72	.202		
	Total	18.017	75			
Co	Between Groups	43.989	3	14.663	2.164	.100
	Within Groups	487.954	72	6.777		
	Total	531.942	75			
Cr	Between Groups	1535.348	3	511.783	7.607	.000
	Within Groups	4843.893	72	67.276		
	Total	6379.241	75			
Cu	Between Groups	834.260	3	278.087	2.644	.056
	Within Groups	7572.698	72	105.176		
	Total	8406.958	75			
Fe	Between Groups	278433518.525	3	92811172.842	3.931	.012
	Within Groups	1700078766.959	72	23612205.097		
	Total	1978512285.483	75			
K	Between Groups	1945361.684	3	648453.895	10.981	.000
	Within Groups	4251864.420	72	59053.673		
	Total	6197226.104	75			
Mg	Between Groups	29081236.602	3	9693745.534	3.192	.029
	Within Groups	218677732.480	72	3037190.729		
	Total	247758969.082	75			

Mn	Between Groups	1620418.380	3	540139.460	22.873	.000
	Within Groups	1700256.867	72	23614.679		
	Total	3320675.247	75			
Ni	Between Groups	762.934	3	254.311	4.595	.005
	Within Groups	3985.039	72	55.348		
	Total	4747.972	75			
P	Between Groups	2735034.963	3	911678.321	14.953	.000
	Within Groups	4389841.858	72	60970.026		
	Total	7124876.820	75			
Pb	Between Groups	2438.434	3	812.811	11.364	.000
	Within Groups	5149.776	72	71.525		
	Total	7588.210	75			
Ti	Between Groups	1623144.964	3	541048.321	24.143	.000
	Within Groups	1613516.883	72	22409.957		
	Total	3236661.847	75			
Zn	Between Groups	5481.924	3	1827.308	4.018	.011
	Within Groups	32744.287	72	454.782		
	Total	38226.211	75			
Na	Between Groups	15648.166	3	5216.055	2.712	.051
	Within Groups	138467.822	72	1923.164		
	Total	154115.988	75			
S	Between Groups	1096383.497	3	365461.166	4.936	.004
	Within Groups	5331075.631	72	74042.717		
	Total	6427459.128	75			

Statistical Analysis of Concentrations of Non-archaeological Features by Case Study

1: Case Study 1; 2: Case Study 3; 3: Case Study 2

Element	Case study	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	1	20702.123	.	.	.	.	20702.123	20702.123
	2	5	30825.181	4434.869	1983.334	25318.562	36331.799	26807.776	38363.870
	3	12	17639.485	2469.709	712.943	16070.306	19208.664	14200.371	23115.426
	Total	18	21472.325	6686.365	1575.991	18147.273	24797.376	14200.371	38363.870
Ca	1	1	3280.962	.	.	.	.	3280.962	3280.962
	2	5	6076.602	2266.623	1013.664	3262.217	8890.986	4374.562	9859.662
	3	12	1400.281	527.884	152.387	1064.879	1735.682	877.332	2369.362
	Total	18	2803.741	2437.909	574.620	1591.397	4016.085	877.332	9859.662
Cd	1	1	2.72800	.	.	.	.	2.728	2.728
	2	5	2.87300	.430424	.192491	2.33856	3.40744	2.285	3.303
	3	12	2.14567	.236976	.068409	1.99510	2.29623	1.610	2.542
	Total	18	2.38006	.444184	.104695	2.15917	2.60094	1.610	3.303
Co	1	1	11.97900	.	.	.	.	11.979	11.979

	2	5	10.63200	2.347733	1.049938	7.71690	13.54710	7.710	13.018
	3	12	9.27708	1.565338	.451874	8.28252	10.27165	6.965	11.713
	Total	18	9.80356	1.886340	.444615	8.86550	10.74161	6.965	13.018
Cr	1	1	53.64800	.	.	.	.	53.648	53.648
	2	5	46.68600	8.361648	3.739443	36.30364	57.06836	38.554	60.504
	3	12	35.90700	3.444650	.994385	33.71837	38.09563	30.033	44.171
	Total	18	39.88678	7.748899	1.826433	36.03334	43.74021	30.033	60.504
Cu	1	1	19.15300	.	.	.	.	19.153	19.153
	2	5	23.87500	25.949845	11.605123	-8.34599	56.09599	10.415	70.239
	3	12	10.62725	3.329601	.961173	8.51172	12.74278	6.387	18.575
	Total	18	14.78083	14.256451	3.360278	7.69127	21.87040	6.387	70.239
Fe	1	1	23017.685	.	.	.	.	23017.685	23017.685
	2	5	20336.248	6866.744	3070.901	11810.059	28862.437	11777.087	27691.656
	3	12	19650.684	3479.442	1004.428	17439.951	21861.416	12686.489	25521.108
	Total	18	20028.174	4425.209	1043.031	17827.569	22228.779	11777.087	27691.656
K	1	1	1225.300	.	.	.	.	1225.3	1225.3
	2	5	1394.060	220.0067	98.3900	1120.886	1667.234	1115.7	1683.2
	3	12	1129.714	458.4589	132.3457	838.423	1421.005	734.1	2137.1
	Total	18	1208.454	402.3880	94.8438	1008.351	1408.557	734.1	2137.1
Mg	1	1	8374.900	.	.	.	.	8374.9	8374.9
	2	5	6726.300	864.8033	386.7518	5652.505	7800.095	5670.4	7490.2
	3	12	5538.325	1222.8836	353.0161	4761.342	6315.308	4322.5	7859.0
	Total	18	6025.906	1334.2718	314.4909	5362.388	6689.423	4322.5	8374.9
Mn	1	1	478.47300	.	.	.	.	478.473	478.473
	2	5	160.34300	62.556406	27.976075	82.66896	238.01704	81.713	239.773
	3	12	329.82883	99.766592	28.800134	266.44016	393.21750	108.743	450.423
	Total	18	291.00744	124.554462	29.357768	229.06797	352.94692	81.713	478.473
Ni	1	1	36.90900	.	.	.	.	36.909	36.909
	2	5	29.29640	3.611959	1.615317	24.81156	33.78124	22.949	31.702
	3	12	23.75283	4.330450	1.250093	21.00140	26.50427	18.601	33.855
	Total	18	26.02361	5.381834	1.268511	23.34729	28.69993	18.601	36.909
P	1	1	1218.500	.	.	.	.	1218.5	1218.5
	2	5	612.480	127.5157	57.0267	454.148	770.812	434.3	754.9
	3	12	565.166	244.4428	70.5646	409.854	720.477	158.4	951.3
	Total	18	614.605	256.2580	60.4006	487.171	742.039	158.4	1218.5
Pb	1	1	39.38100	.	.	.	.	39.381	39.381
	2	5	17.78160	6.912517	3.091371	9.19858	26.36462	9.205	25.025
	3	12	14.86883	8.059397	2.326548	9.74814	19.98953	4.307	27.915
	Total	18	17.03972	9.280156	2.187354	12.42481	21.65464	4.307	39.381

Tl	1	1	630.999	.	.	.	.	630.999	630.999
	2	5	215.957	84.341	37.718	111.232	320.681	116.999	312.509
	3	12	565.414	199.181	57.498	438.860	691.968	389.579	1114.429
	Total	18	471.986	232.966	54.910	356.135	587.838	116.999	1114.429
Zn	1	1	79.5100	.	.	.	.	79.51	79.51
	2	5	51.2292	10.76599	4.81470	37.8615	64.5969	37.52	59.86
	3	12	42.5474	9.63662	2.78185	36.4246	48.6702	26.87	61.08
	Total	18	47.0125	12.99178	3.06219	40.5518	53.4732	26.87	79.51
Na	1	1	161.37100	.	.	.	.	161.371	161.371
	2	5	116.55100	22.023184	9.849067	89.20560	143.89640	91.421	140.351
	3	12	71.17200	18.280443	5.277109	59.55716	82.78684	53.376	109.311
	Total	18	88.78833	32.954601	7.767474	72.40040	105.17627	53.376	161.371
S	1	1	478.339	.	.	.	.	478.339	478.339
	2	5	680.611	583.821	261.092	-44.299	1405.521	157.929	1528.089
	3	12	248.983	140.206	40.474	159.900	338.066	70.660	449.819
	Total	18	381.622	363.566	85.693	200.824	562.419	70.660	1528.089

Statistical Analysis of Concentrations of Non-archaeological Features by Case Study.
Significance Level = 0.005

<i>Element</i>		<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
Al	Between Groups	614260706.829	2	307130353.414	31.605	.000
	Within Groups	145766418.918	15	9717761.261		
	Total	760027125.747	17			
Ca	Between Groups	77422229.555	2	38711114.777	24.588	.000
	Within Groups	23615608.554	15	1574373.904		
	Total	101037838.109	17			
Cd	Between Groups	1.995	2	.998	11.013	.001
	Within Groups	1.359	15	.091		
	Total	3.354	17			
Co	Between Groups	11.490	2	5.745	1.759	.206
	Within Groups	49.001	15	3.267		
	Total	60.491	17			
Cr	Between Groups	610.582	2	305.291	11.164	.001
	Within Groups	410.190	15	27.346		
	Total	1020.772	17			
Cu	Between Groups	639.662	2	319.831	1.704	.215
	Within Groups	2815.526	15	187.702		
	Total	3455.189	17			
Fe	Between Groups	11121708.845	2	5560854.423	.259	.775
	Within Groups	321780432.153	15	21452028.810		
	Total	332902140.998	17			

K	Between Groups	246931.260	2	123465.630	.739	.494
	Within Groups	2505642.225	15	167042.815		
	Total	2752573.485	17			
Mg	Between Groups	10823354.367	2	5411677.183	4.175	.036
	Within Groups	19441426.263	15	1296095.084		
	Total	30264780.629	17			
Mn	Between Groups	138594.523	2	69297.261	8.306	.004
	Within Groups	125140.317	15	8342.688		
	Total	263734.840	17			
Ni	Between Groups	233.925	2	116.962	6.788	.008
	Within Groups	258.466	15	17.231		
	Total	492.390	17			
P	Between Groups	394042.524	2	197021.262	4.091	.038
	Within Groups	722316.209	15	48154.414		
	Total	1116358.732	17			
Pb	Between Groups	558.438	2	279.219	4.625	.027
	Within Groups	905.624	15	60.375		
	Total	1464.062	17			
Tl	Between Groups	457786.741	2	228893.371	7.386	.006
	Within Groups	464860.471	15	30990.698		
	Total	922647.213	17			
Zn	Between Groups	1384.234	2	692.117	6.990	.007
	Within Groups	1485.134	15	99.009		
	Total	2869.368	17			
Na	Between Groups	12846.094	2	6423.047	17.156	.000
	Within Groups	5616.003	15	374.400		
	Total	18462.097	17			
S	Between Groups	667441.949	2	333720.974	3.169	.071
	Within Groups	1579628.041	15	105308.536		
	Total	2247069.990	17			

Case Study 2: Statistical Analysis of Soil Elemental Concentrations

1: Exterior; 2: Outer ditch; 3: Outer ditch reverse anomaly/bank; 4: Inter-ditch; 5: Inner ditch; 6: Inner ditch branch; 7: Interior

Element	Feature	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	1	20702.123	.	.	.	.	20702.123	20702.123
	2	1	21602.959	.	.	.	.	21602.959	21602.959
	3	2	20478.195	44.884	31.738	20074.925	20881.464	20446.457	20509.933
	4	5	19543.387	1266.161	566.244	17971.240	21115.534	17945.729	21384.943
	5	4	21272.343	1088.150	544.075	19540.853	23003.833	19887.193	22547.944
	6	1	19615.372	.	.	.	.	19615.372	19615.372
	7	8	19307.315	613.183	216.793	18794.680	19819.949	18244.239	20122.682

	Total	22	20006.439	1146.881	244.515	19497.941	20514.938	17945.729	22547.944
Ca	1	1	3280.962	.	.	.	.	3280.962	3280.962
	2	1	3826.262	.	.	.	.	3826.262	3826.262
	3	2	2574.962	32.809	23.200	2280.178	2869.745	2551.762	2598.162
	4	5	3257.122	313.415	140.163	2867.965	3646.278	2778.462	3637.262
	5	4	3735.937	617.478	308.739	2753.391	4718.482	2831.962	4215.262
	6	1	3034.162	.	.	.	.	3034.162	3034.162
	7	8	3150.824	722.797	255.547	2546.550	3755.098	2414.262	4205.762
	Total	22	3260.330	597.892	127.471	2995.239	3525.420	2414.262	4215.262
Cd	1	1	2.72800	.	.	.	.	2.728	2.728
	2	1	2.83200	.	.	.	.	2.832	2.832
	3	2	2.70150	.026163	.018500	2.46644	2.93656	2.683	2.720
	4	5	2.86160	.274859	.122921	2.52032	3.20288	2.526	3.166
	5	4	3.06475	.339246	.169623	2.52493	3.60457	2.727	3.536
	6	1	2.95300	.	.	.	.	2.953	2.953
	7	8	2.98775	.117033	.041378	2.88991	3.08559	2.849	3.195
	Total	22	2.92659	.220586	.047029	2.82879	3.02439	2.526	3.536
Co	1	1	11.97900	.	.	.	.	11.979	11.979
	2	1	12.09900	.	.	.	.	12.099	12.099
	3	2	12.15150	.697914	.493500	5.88099	18.42201	11.658	12.645
	4	5	12.78640	.994404	.444711	11.55168	14.02112	11.531	14.004
	5	4	14.95900	2.026663	1.013332	11.73413	18.18387	12.768	17.475
	6	1	13.96700	.	.	.	.	13.967	13.967
	7	8	14.19788	1.099294	.388659	13.27884	15.11691	12.524	15.552
	Total	22	13.62268	1.511557	.322265	12.95250	14.29287	11.531	17.475
Cr	1	1	53.64800	.	.	.	.	53.648	53.648
	2	1	53.39900	.	.	.	.	53.399	53.399
	3	2	50.973	1.7147	1.212	35.567	66.379	49.761	52.186
	4	5	53.106	4.839	2.164	47.096	59.115	48.772	60.053
	5	4	57.556	3.755	1.877	51.579	63.532	52.188	60.956
	6	1	53.429	.	.	.	.	53.429	53.429
	7	8	52.824	4.262	1.507	49.261	56.388	46.263	58.532
	Total	22	53.671	4.073	.868	51.865	55.47789	46.263	60.956
Cu	1	1	19.15300	.	.	.	.	19.153	19.153
	2	1	19.20800	.	.	.	.	19.208	19.208
	3	2	17.53400	.439820	.311000	13.58237	21.48563	17.223	17.845
	4	5	20.40380	3.434470	1.535942	16.13934	24.66826	17.375	24.215
	5	4	22.49325	1.088107	.544054	20.76183	24.22467	21.632	24.082
	6	1	31.59700	.	.	.	.	31.597	31.597
	7	8	23.21125	2.043085	.722340	21.50319	24.91931	19.770	26.113
	Total	22	21.94127	3.473807	.740618	20.40107	23.48147	17.223	31.597
Fe	1	1	23017.685	.	.	.	.	23017.685	23017.685
	2	1	25363.756	.	.	.	.	25363.756	25363.756
	3	2	25551.955	3442.663	2434.331	-5379.153	56483.063	23117.624	27986.286
	4	5	26015.969	1704.478	762.265	23899.579	28132.358	24519.906	28023.810
	5	4	29163.954	3290.928	1645.464	23927.352	34400.555	25861.458	33622.599

	6	1	27049.236	.	.	.	.	27049.236	27049.236
	7	8	28459.386	1496.146	528.967	27208.576	29710.195	26599.933	31163.494
	Total	22	27315.697	2514.559	536.105	26200.804	28430.590	23017.685	33622.599
K	1	1	1225.300	.	.	.	.	1225.3	1225.3
	2	1	1184.700	.	.	.	.	1184.7	1184.7
	3	2	1225.400	2.5456	1.8000	1202.529	1248.271	1223.6	1227.2
	4	5	1239.060	119.5222	53.4520	1090.654	1387.466	1098.5	1391.4
	5	4	1414.375	143.3008	71.6504	1186.351	1642.399	1203.0	1517.5
	6	1	1404.100	.	.	.	.	1404.1	1404.1
	7	8	1372.150	88.8355	31.4081	1297.882	1446.418	1244.2	1552.0
	Total	22	1322.495	122.7162	26.1632	1268.086	1376.905	1098.5	1552.0
Mg	1	1	8374.900	.	.	.	.	8374.9	8374.9
	2	1	8542.800	.	.	.	.	8542.8	8542.8
	3	2	8157.450	333.1180	235.5500	5164.503	11150.397	7921.9	8393.0
	4	5	8590.180	847.1435	378.8541	7538.312	9642.048	7876.6	9889.6
	5	4	10212.489	1403.3223	701.6611	7979.490	12445.488	8351.9	11724.6
	6	1	8280.200	.	.	.	.	8280.2	8280.2
	7	8	8853.151	914.4579	323.3097	8088.645	9617.657	7739.5	10716.8
	Total	22	8915.403	1069.4051	227.9979	8441.255	9389.551	7739.5	11724.6
Mn	1	1	478.47300	.	.	.	.	478.473	478.473
	2	1	520.12300	.	.	.	.	520.123	520.123
	3	2	499.768	15.238	10.775	362.858	636.677	488.993	510.543
	4	5	580.833	53.771	24.047	514.066	647.599	516.993	626.823
	5	4	672.840	40.956	20.478	607.670	738.010	628.683	718.563
	6	1	729.513	.	.	.	.	729.513	729.513
	7	8	707.918	80.386	28.420	640.713	775.122	581.153	804.583
	Total	22	635.750	99.568	21.228	591.604	679.896	478.473	804.583
Ni	1	1	36.90900	.	.	.	.	36.909	36.909
	2	1	36.42500	.	.	.	.	36.425	36.425
	3	2	36.52350	1.663822	1.176500	21.57465	51.47235	35.347	37.700
	4	5	39.86520	5.030851	2.249865	33.61857	46.11183	34.670	45.211
	5	4	44.47775	5.389345	2.694672	35.90210	53.05340	38.987	51.590
	6	1	38.95600	.	.	.	.	38.956	38.956
	7	8	42.30325	3.539242	1.251311	39.34437	45.26213	38.129	47.399
	Total	22	40.95455	4.520366	.963745	38.95033	42.95876	34.670	51.590
P	1	1	1218.500	.	.	.	.	1218.5	1218.5
	2	1	1278.900	.	.	.	.	1278.9	1278.9
	3	2	1106.000	35.7796	25.3000	784.533	1427.467	1080.7	1131.3
	4	5	1241.700	89.8983	40.2037	1130.077	1353.323	1144.2	1379.6
	5	4	1160.000	105.5894	52.7947	991.984	1328.016	1034.8	1287.2
	6	1	1454.900	.	.	.	.	1454.9	1454.9
	7	8	1309.911	278.0032	98.2890	1077.495	1542.328	866.3	1666.1
	Total	22	1249.640	189.5853	40.4197	1165.583	1333.698	866.3	1666.1
Pb	1	1	39.38100	.	.	.	.	39.381	39.381
	2	1	40.30900	.	.	.	.	40.309	40.309
	3	2	31.43300	.830143	.587000	23.97446	38.89154	30.846	32.020

	4	5	33.15040	4.547762	2.033821	27.50361	38.79719	28.715	38.215
	5	4	38.75575	3.929225	1.964613	32.50348	45.00802	33.183	42.194
	6	1	43.06200	.	.	.	.	43.062	43.062
	7	8	34.88913	7.823317	2.765960	28.34867	41.42958	19.427	42.743
	Total	22	35.70482	6.010637	1.281472	33.03985	38.36979	19.427	43.062
Ti	1	1	630.999	.	.	.	.	630.999	630.999
	2	1	662.519	.	.	.	.	662.519	662.519
	3	2	583.254	35.984	25.445	259.944	906.563	557.809	608.699
	4	5	620.765	90.570	40.504	508.306	733.223	524.239	759.059
	5	4	758.791	155.656	77.828	511.107	1006.475	536.359	878.559
	6	1	565.799	.	.	.	.	565.799	565.799
	7	8	624.175	84.405	29.841	553.610	694.740	527.469	741.289
	Total	22	643.555	104.475	22.274	597.233	689.877	524.239	878.559
Zn	1	1	79.5100	.	.	.	.	79.51	79.51
	2	1	84.5780	.	.	.	.	84.58	84.58
	3	2	75.6825	6.39295	4.52050	18.2441	133.1209	71.16	80.20
	4	5	76.4456	11.52864	5.15577	62.1309	90.7603	65.06	95.82
	5	4	82.1877	3.27805	1.63903	76.9716	87.4039	77.32	84.13
	6	1	86.7450	.	.	.	.	86.75	86.75
	7	8	81.4421	9.95729	3.52044	73.1176	89.7666	60.96	92.99
	Total	22	80.2143	8.45350	1.80229	76.4662	83.9623	60.96	95.82
Na	1	1	161.371	.	.	.	.	161.371	161.371
	2	1	193.641	.	.	.	.	193.641	193.641
	3	2	166.186	20.216	14.295	-15.449	347.821	151.891	180.481
	4	5	171.547	37.631	16.829	124.821	218.272	123.431	219.191
	5	4	216.328	61.690	30.845	118.165	314.49	134.101	283.721
	6	1	139.591	.	.	.	.	139.591	139.591
	7	8	142.931	30.508	10.786	117.425	168.436	93.571	179.021
	Total	22	167.885	43.618	9.299	148.545	187.224	93.571	283.721
S	1	1	478.339	.	.	.	.	478.339	478.339
	2	1	461.859	.	.	.	.	461.859	461.859
	3	2	443.489	25.512	18.040	214.269	672.708	425.449	461.529
	4	5	479.851	38.863	17.380	431.594	528.107	421.239	525.919
	5	4	409.226	56.307	28.153	319.627	498.825	329.899	449.549
	6	1	488.689	.	.	.	.	488.689	488.689
	7	8	470.801	140.871	49.805	353.030	588.572	235.959	648.589
	Total	22	459.929	89.984	19.184	420.032	499.825	235.959	648.589

Case Study 2: Statistical analysis of variance of soil elemental concentrations
Significance level = 0.005

Element		Sum of Squares	df	Mean Square	F	Sig.
Al	Between Groups	15023224.662	6	2503870.777	2.981	.040
	Within Groups	12598849.149	15	839923.277		
	Total	27622073.811	21			
Ca	Between Groups	2312106.429	6	385351.072	1.113	.400
	Within Groups	5194884.758	15	346325.651		
	Total	7506991.188	21			
Cd	Between Groups	.278	6	.046	.933	.500
	Within Groups	.744	15	.050		
	Total	1.022	21			
Co	Between Groups	22.757	6	3.793	2.256	.094
	Within Groups	25.224	15	1.682		
	Total	47.981	21			
Cr	Between Groups	82.383	6	13.730	.774	.603
	Within Groups	266.142	15	17.743		
	Total	348.524	21			
Cu	Between Groups	173.267	6	28.878	5.405	.004
	Within Groups	80.147	15	5.343		
	Total	253.414	21			
Fe	Between Groups	61150432.609	6	10191738.768	2.134	.110
	Within Groups	71632734.985	15	4775515.666		
	Total	132783167.593	21			
K	Between Groups	142248.270	6	23708.045	2.044	.123
	Within Groups	173996.279	15	11599.752		
	Total	316244.550	21			
Mg	Between Groups	9273022.729	6	1545503.788	1.572	.223
	Within Groups	14743148.395	15	982876.560		
	Total	24016171.124	21			
Mn	Between Groups	146127.334	6	24354.556	5.886	.003
	Within Groups	62063.478	15	4137.565		
	Total	208190.811	21			
Mo	Between Groups	.012	6	.002	.	.
	Within Groups	.000	15	.000		
	Total	.012	21			
Ni	Between Groups	150.283	6	25.047	1.347	.297
	Within Groups	278.825	15	18.588		
	Total	429.108	21			
P	Between Groups	146739.939	6	24456.657	.603	.724
	Within Groups	608054.761	15	40536.984		
	Total	754794.700	21			

Element		Sum of Squares	df	Mean Square	F	Sig.
Pb	Between Groups	200.519	6	33.420	.898	.521
	Within Groups	558.164	15	37.211		
	Total	758.683	21			
Ti	Between Groups	72555.025	6	12092.504	1.158	.378
	Within Groups	156664.218	15	10444.281		
	Total	229219.243	21			
Zn	Between Groups	201.916	6	33.653	.389	.875
	Within Groups	1298.779	15	86.585		
	Total	1500.695	21			
Na	Between Groups	15947.886	6	2657.981	1.661	.199
	Within Groups	24005.584	15	1600.372		
	Total	39953.471	21			
S	Between Groups	14923.432	6	2487.239	.241	.956
	Within Groups	155117.000	15	10341.133		
	Total	170040.432	21			

Case Study 1: Statistical analysis of means of concentrations in excavated and augured soils

1: Excavated soil samples; 2: Augured soil samples

Element	Sample type	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	15	17091.281	2003.649	517.340	15981.697	18200.865	14200.371	23115.426
	2	43	17274.131	1537.129	234.410	16801.073	17747.190	14918.998	23228.302
	Total	58	17226.843	1653.346	217.095	16792.117	17661.568	14200.371	23228.302
Ca	1	15	1306.566	497.849	128.544	1030.866	1582.265	774.992	2369.362
	2	43	1576.960	350.4044	53.436	1469.122	1684.799	923.202	2206.162
	Total	58	1507.030	406.955	53.435	1400.027	1614.034	774.992	2369.362
Cd	1	15	2.10340	.256533	.066236	1.96134	2.24546	1.558	2.542
	2	43	2.23786	.300615	.045843	2.14534	2.33038	1.663	3.309
	Total	58	2.20309	.293732	.038569	2.12585	2.28032	1.558	3.309
Co	1	15	8.90567	1.775858	.458525	7.92223	9.88910	5.255	11.713
	2	43	9.86777	2.285593	.348550	9.16437	10.57117	6.932	15.596
	Total	58	9.61895	2.191892	.287810	9.04262	10.19528	5.255	15.596
Cr	1	15	34.88287	3.608496	.931710	32.88455	36.88119	30.033	44.171
	2	43	35.86291	3.272038	.498981	34.85592	36.86989	30.553	47.476
	Total	58	35.60945	3.357736	.440892	34.72658	36.49232	30.033	47.476
Cu	1	15	10.46693	3.083550	.796169	8.75932	12.17455	6.387	18.575
	2	43	10.74230	1.615195	.246315	10.24522	11.23939	7.840	15.699
	Total	58	10.67109	2.066997	.271410	10.12760	11.21458	6.387	18.575

Element	Sample type	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Fe	1	15	19252.099	3477.889	897.987	17326.108	21178.090	12475.710	25521.108
	2	43	20929.161	3523.302	537.298	19844.848	22013.473	15684.322	31461.421
	Total	58	20495.438	3559.003	467.320	19559.645	21431.230	12475.710	31461.421
K	1	15	1062.830	429.711	110.950	824.863	1300.796	734.12	2137.10
	2	43	955.478	157.776	24.060	906.921	1004.034	746.17	1652.70
	Total	58	983.241	256.795	33.718	915.720	1050.762	734.12	2137.10
Mg	1	15	5228.067	1262.234	325.907	4529.065	5927.069	3418.0	7859.0
	2	43	5472.163	1194.912	182.222	5104.424	5839.903	4111.5	10223.2
	Total	58	5409.035	1206.2420	158.387	5091.870	5726.200	3418.0	10223.2
Mn	1	15	306.222	109.047	28.155	245.834	366.611	97.592	450.423
	2	43	377.660	131.085	19.990	337.318	418.002	155.623	694.723
	Total	58	359.185	128.754	16.906	325.331	393.039	97.592	694.723
Ni	1	15	23.326	4.824	1.245	20.654	25.997	15.662	33.855
	2	43	25.100	4.544	.692	23.701	26.498	19.598	39.385
	Total	58	24.641	4.641	.609	23.421	25.862	15.662	39.385
P	1	15	567.285	232.0060	59.9037	438.805	695.766	158.4	951.3
	2	43	685.210	173.3328	26.4330	631.866	738.554	438.5	965.7
	Total	58	654.712	195.1195	25.6204	603.408	706.016	158.4	965.7
Pb	1	15	15.172	7.391	1.908	11.078	19.265	4.307	27.915
	2	43	16.760	5.658	.862	15.018	18.501	8.060	32.536
	Total	58	16.349	6.123	.804	14.739	17.959	4.307	32.536
Ti	1	15	540.755	193.894	50.063	433.379	648.130	364.279	1114.429
	2	43	565.550	147.040	22.423	520.297	610.802	388.729	877.649
	Total	58	559.137	159.012	20.879	517.327	600.947	364.279	1114.429
Zn	1	15	39.904	10.079	2.602	34.322	45.486	24.452	61.079
	2	43	47.023	20.746	3.163	40.638	53.407	35.842	173.915
	Total	58	45.182	18.761	2.463	40.249	50.115	24.452	173.915
Na	1	15	66.347	18.899	4.879	55.881	76.813	43.374	109.311
	2	43	79.330	17.742	2.705	73.870	84.791	54.690	132.651
	Total	58	75.972	18.777	2.465	71.035	80.910	43.374	132.651
S	1	15	262.243	130.856	33.786	189.778	334.709	70.660	449.819
	2	43	330.157	120.631	18.396	293.032	367.282	87.881	562.219
	Total	58	312.593	125.809	16.519	279.513	345.673	70.660	562.219

Case Study 1: Statistical analysis of variance of concentrations in excavated and augured soils.

Significance levels = 0.005

Element		Sum of Squares	df	Mean Square	F	Sig.
Al	Between Groups	371810.948	1	371810.948	.134	.716
	Within Groups	155440825.934	56	2775729.035		
	Total	155812636.882	57			
Ca	Between Groups	813069.676	1	813069.676	5.278	.025
	Within Groups	8626857.261	56	154051.023		
	Total	9439926.937	57			
Cd	Between Groups	.201	1	.201	2.387	.128
	Within Groups	4.717	56	.084		
	Total	4.918	57			
Co	Between Groups	10.294	1	10.294	2.187	.145
	Within Groups	263.557	56	4.706		
	Total	273.850	57			
Cr	Between Groups	10.681	1	10.681	.946	.335
	Within Groups	631.959	56	11.285		
	Total	642.640	57			
Cu	Between Groups	.843	1	.843	.195	.661
	Within Groups	242.688	56	4.334		
	Total	243.531	57			
Fe	Between Groups	31277336.764	1	31277336.764	2.536	.117
	Within Groups	690713687.243	56	12334172.986		
	Total	721991024.007	57			
K	Between Groups	128159.520	1	128159.520	1.977	.165
	Within Groups	3630648.958	56	64833.017		
	Total	3758808.478	57			
Mg	Between Groups	662606.167	1	662606.167	.451	.505
	Within Groups	82273518.724	56	1469169.977		
	Total	82936124.892	57			
Mn	Between Groups	56752.781	1	56752.781	3.578	.064
	Within Groups	888180.228	56	15860.361		
	Total	944933.009	57			
Ni	Between Groups	35.010	1	35.010	1.643	.205
	Within Groups	1193.135	56	21.306		
	Total	1228.145	57			
P	Between Groups	154647.445	1	154647.445	4.297	.043
	Within Groups	2015434.206	56	35989.897		
	Total	2170081.651	57			

Element		Sum of Squares	df	Mean Square	F	Sig.
Pb	Between Groups	28.049	1	28.049	.745	.392
	Within Groups	2109.591	56	37.671		
	Total	2137.640	57			
Ti	Between Groups	6837.001	1	6837.001	.267	.607
	Within Groups	1434412.634	56	25614.511		
	Total	1441249.635	57			
Zn	Between Groups	563.547	1	563.547	1.618	.209
	Within Groups	19499.657	56	348.208		
	Total	20063.203	57			
Na	Between Groups	1874.524	1	1874.524	5.761	.020
	Within Groups	18222.334	56	325.399		
	Total	20096.859	57			
S	Between Groups	51291.657	1	51291.657	3.376	.071
	Within Groups	850910.439	56	15194.829		
	Total	902202.096	57			

Case Study 1: statistical analysis of means of concentrations of archaeological features

1: Topsoil; 2: Entrance; 3: Ditch; 4: Bank; 5: Interior; 6: Natural

Element	Feature	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	4	16751.669	3131.724	1565.862	11768.396	21734.942	14200.371	21320.878
	2	3	18140.051	546.436	315.485	16782.628	19497.475	17531.962	18589.915
	3	18	17196.218	1176.695	277.349	16611.062	17781.375	15515.756	20773.850
	4	20	16861.968	1698.054	379.696	16067.254	17656.682	14918.998	23228.302
	5	4	16904.002	139.135	69.567	16682.607	17125.397	16757.940	17080.529
	6	8	18083.393	2169.322	766.971	16269.793	19896.992	15931.345	23115.426
	Total	57	17201.426	1656.571	219.418	16761.878	17640.974	14200.371	23228.302
Ca	1	4	2046.612	382.487	191.243	1437.989	2655.234	1526.962	2369.362
	2	3	1936.728	229.575	132.545	1366.432	2507.024	1754.462	2194.562
	3	18	1485.697	370.102	87.233	1301.649	1669.744	774.992	2206.162
	4	20	1529.594	403.494	90.224	1340.752	1718.435	923.202	2123.162
	5	4	1423.887	121.699	60.849	1230.235	1617.538	1277.762	1529.962
	6	8	1077.115	130.892	46.277	967.686	1186.544	877.332	1247.662
	Total	57	1502.518	409.106	54.187	1393.967	1611.068	774.992	2369.362

Element	Feature	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
Cd	1	4	2.14300	.156431	.078216	1.89408	2.39192	1.942	2.324
	2	3	2.11433	.125803	.072632	1.80182	2.42684	1.977	2.224
	3	18	2.18200	.341620	.080521	2.01212	2.35188	1.558	2.850
	4	20	2.27060	.313536	.070109	2.12386	2.41734	1.829	3.309
	5	4	2.11550	.192812	.096406	1.80869	2.42231	1.849	2.292
	6	8	2.14700	.278844	.098586	1.91388	2.38012	1.610	2.542
	Total	57	2.19721	.292884	.038793	2.11950	2.27492	1.558	3.309
Co	1	4	8.41225	.813250	.406625	7.11819	9.70631	7.586	9.298
	2	3	7.72833	.656441	.378996	6.09764	9.35902	7.191	8.460
	3	18	9.12789	2.245751	.529329	8.01110	10.24467	5.255	15.596
	4	20	10.58205	2.559815	.572392	9.38402	11.78008	6.932	15.272
	5	4	9.43100	.457439	.228720	8.70311	10.15889	8.757	9.761
	6	8	9.70950	1.710529	.604763	8.27946	11.13954	6.965	11.713
	Total	57	9.61714	2.211333	.292898	9.03039	10.20389	5.255	15.596
Cr	1	4	33.68175	2.853400	1.426700	29.14135	38.22215	30.033	36.495
	2	3	37.78067	1.921827	1.109567	33.00658	42.55475	36.514	39.992
	3	18	35.16767	3.873975	.913105	33.24118	37.09415	30.214	47.476
	4	20	35.26765	3.298239	.737509	33.72403	36.81127	30.553	45.352
	5	4	35.72375	1.121291	.560646	33.93953	37.50797	34.919	37.360
	6	8	37.01963	3.303367	1.167916	34.25794	39.78131	33.508	44.171
	Total	57	35.53495	3.338870	.442244	34.64903	36.42087	30.033	47.476
Cu	1	4	10.89875	1.513266	.756633	8.49081	13.30669	9.877	13.148
	2	3	10.23767	.478857	.276468	9.04812	11.42721	9.842	10.770
	3	18	10.48661	1.939763	.457207	9.52199	11.45123	7.452	14.687
	4	20	10.68840	1.476892	.330243	9.99719	11.37961	8.688	15.699
	5	4	12.15375	1.216532	.608266	10.21798	14.08952	11.055	13.568
	6	8	10.49150	4.046806	1.430762	7.10829	13.87471	6.387	18.575
	Total	57	10.69091	2.079799	.275476	10.13907	11.24276	6.387	18.575
Fe	1	4	17971.979	2034.280	1017.140	14734.985	21208.974	15684.322	20036.057
	2	3	18800.336	523.895	302.471	17498.906	20101.765	18235.380	19270.125
	3	18	19875.295	3607.889	850.387	18081.134	21669.456	12475.710	28156.707
	4	20	21706.812	3972.592	888.298	19847.582	23566.043	16486.690	31461.421
	5	4	20367.001	1469.660	734.830	18028.443	22705.559	18525.647	21897.054
	6	8	20490.036	3851.688	1361.777	17269.943	23710.128	12686.489	25521.108
	Total	57	20448.575	3572.5406	473.194	19500.652	21396.498	12475.710	31461.421
K	1	4	831.8975	33.11173	16.55586	779.2094	884.5856	786.10	857.23
	2	3	882.8300	43.04558	24.85237	775.8989	989.7611	847.23	930.67
	3	18	915.2594	138.55695	32.65819	846.3567	984.1622	742.63	1287.30
	4	20	984.0160	191.83154	42.89484	894.2361	1073.7959	769.22	1652.70
	5	4	892.8400	18.97377	9.48688	862.6485	923.0315	879.07	920.22
	6	8	1278.6225	503.78179	178.11376	857.4504	1699.7946	734.12	2137.10
	Total	57	981.2528	258.62731	34.25602	912.6297	1049.8759	734.12	2137.10

Mg	1	4	4739.900	494.6026	247.3013	3952.877	5526.923	4322.5	5374.0
	2	3	4492.100	448.3952	258.8811	3378.225	5605.975	4111.5	4986.4
	3	18	5233.800	1314.0501	309.7246	4580.338	5887.262	3418.0	8970.5
	4	20	5666.201	1278.9367	285.9789	5067.640	6264.762	4314.1	10223.2
	5	4	5099.850	396.3878	198.1939	4469.109	5730.591	4537.2	5441.9
	6	8	5937.538	1303.3527	460.8048	4847.907	7027.168	4473.3	7859.0
	Total	57	5401.193	1215.4720	160.9932	5078.685	5723.702	3418.0	10223.2
Mn	1	4	340.86550	73.704856	36.852428	223.58463	458.14637	295.773	450.423
	2	3	236.31967	15.562392	8.984951	197.66054	274.97879	221.763	252.723
	3	18	323.724	143.062	33.720	252.581	394.867	97.592	694.723
	4	20	423.723	128.507	28.735	363.580	483.866	216.973	651.013
	5	4	357.310	44.386	22.1933	286.681	427.939	303.923	412.613
	6	8	324.310	114.927	40.633	228.228	420.392	108.743	424.133
	Total	57	357.853	129.495	17.1521	323.493	392.21	97.592	694.723
Ni	1	4	21.23575	.632301	.316150	20.22962	22.24188	20.468	22.016
	2	3	22.18700	.868803	.501604	20.02877	24.34523	21.190	22.782
	3	18	23.90906	5.009718	1.180802	21.41778	26.40033	15.662	37.725
	4	20	26.26020	5.078590	1.135607	23.88335	28.63705	19.601	39.385
	5	4	23.94500	1.774961	.887481	21.12064	26.76936	21.603	25.893
	6	8	25.01137	4.885359	1.727235	20.92711	29.09564	18.601	33.855
	Total	57	24.61302	4.677931	.619607	23.37180	25.85424	15.662	39.385
P	1	4	867.6025	76.08999	38.04499	746.5263	988.6787	781.14	951.30
	2	3	892.6333	21.11601	12.19134	840.1782	945.0884	876.49	916.53
	3	18	648.3600	155.56151	36.66620	571.0011	725.7189	415.49	965.68
	4	20	655.0830	199.29123	44.56287	561.8118	748.3542	438.50	954.13
	5	4	775.9450	81.74299	40.87149	645.8737	906.0163	710.29	890.50
	6	8	413.9475	114.07925	40.33310	318.5749	509.3201	158.38	541.90
	Total	57	655.0142	196.84024	26.07213	602.7855	707.2430	158.38	965.68
Pb	1	4	22.02050	6.271374	3.135687	12.04134	31.99966	15.718	27.915
	2	3	22.98300	.686758	.396500	21.27700	24.68900	22.195	23.454
	3	18	16.55200	3.717313	.876179	14.70342	18.40058	8.940	23.645
	4	20	15.16720	6.920259	1.547417	11.92842	18.40598	8.060	32.536
	5	4	20.52900	2.527949	1.263974	16.50647	24.55153	17.590	23.667
	6	8	11.29300	6.432333	2.274173	5.91544	16.67056	4.307	21.565
	Total	57	16.32932	6.176415	.818086	14.69049	17.96814	4.307	32.536
Ti	1	4	434.631	63.094	31.547	334.233	535.029	389.579	525.289
	2	3	418.465	27.775	16.035	349.468	487.462	397.889	450.059
	3	18	541.427	162.086	38.204	460.823	622.030	364.279	877.649
	4	20	606.643	147.854	33.061	537.445	675.841	388.729	848.609
	5	4	476.809	23.016	11.508	440.185	513.432	443.949	493.509
	6	8	630.806	214.422	75.809	451.545	810.067	434.489	1114.429
	Total	57	558.353	160.313	21.234	515.817	600.890	364.279	1114.429
Zn	1	4	44.95300	7.129007	3.564503	33.60916	56.29684	39.625	55.362
	2	3	45.97967	3.497863	2.019492	37.29049	54.66884	42.625	49.605
	3	18	47.27039	32.042774	7.552554	31.33589	63.20489	24.452	173.915
	4	20	45.27680	8.258059	1.846558	41.41191	49.14169	35.842	66.121

	5	4	42.75650	5.138507	2.569253	34.57999	50.93301	38.138	48.609
	6	8	41.34462	10.917344	3.859864	32.21750	50.47175	26.871	61.079
	Total	57	45.19188	18.927912	2.507063	40.16963	50.21413	24.452	173.915
Na	1	4	59.82525	6.259266	3.129633	49.86536	69.78514	53.376	66.642
	2	3	77.65967	17.692135	10.214559	33.70997	121.60937	63.618	97.531
	3	18	74.12028	18.608465	4.386057	64.86651	83.37405	43.374	98.641
	4	20	83.95930	19.013959	4.251651	75.06049	92.85811	55.858	132.651
	5	4	57.23125	1.854652	.927326	54.28008	60.18242	54.690	59.102
	6	8	76.84537	19.949553	7.053232	60.16713	93.52362	57.192	109.311
	Total	57	75.95296	18.943311	2.509103	70.92663	80.97930	43.374	132.651
S	1	4	403.23150	34.978999	17.489499	347.57211	458.89089	368.159	449.819
	2	3	534.77567	16.423670	9.482210	493.97701	575.57432	524.369	553.709
	3	18	339.28733	87.590954	20.645386	295.72938	382.84529	191.849	562.219
	4	20	278.80610	126.25232	28.230877	219.71820	337.89400	87.881	461.819
	5	4	372.01900	30.322431	15.161215	323.76925	420.26875	341.459	413.959
	6	8	171.85950	99.865857	35.307912	88.36955	255.34945	70.660	305.489
	Total	57	311.64033	126.71656	16.784019	278.01790	345.26276	70.660	562.219

Case study 1: statistical analysis of variance of concentrations of archaeological features.

Significance level = 0.005

Element		Sum of Squares	df	Mean Square	F	Sig.
Al	Between Groups	12334063.391	5	2466812.678	.890	.495
	Within Groups	141342860.249	51	2771428.632		
	Total	153676923.639	56			
Ca	Between Groups	3241992.988	5	648398.598	5.394	.000
	Within Groups	6130605.306	51	120207.947		
	Total	9372598.293	56			
Cd	Between Groups	.191	5	.038	.423	.831
	Within Groups	4.613	51	.090		
	Total	4.804	56			
Co	Between Groups	39.646	5	7.929	1.727	.145
	Within Groups	234.193	51	4.592		
	Total	273.840	56			
Element		Sum of Squares	df	Mean Square	F	Sig.
Cr	Between Groups	50.501	5	10.100	.898	.490
	Within Groups	573.790	51	11.251		
	Total	624.291	56			

Cu	Between Groups	10.418	5	2.084	.458	.805
	Within Groups	231.813	51	4.545		
	Total	242.232	56			
Fe	Between Groups	70303467.075	5	14060693.415	1.113	.365
	Within Groups	644427133.639	51	12635826.150		
	Total	714730600.714	56			
K	Between Groups	935531.285	5	187106.257	3.396	.010
	Within Groups	2810201.615	51	55101.992		
	Total	3745732.900	56			
Mg	Between Groups	8802092.189	5	1760418.438	1.214	.316
	Within Groups	73930750.025	51	1449622.550		
	Total	82732842.214	56			
Mn	Between Groups	162211.226	5	32442.245	2.130	.077
	Within Groups	776858.732	51	15232.524		
	Total	939069.958	56			
Ni	Between Groups	129.519	5	25.904	1.205	.320
	Within Groups	1095.931	51	21.489		
	Total	1225.450	56			
P	Between Groups	874363.069	5	174872.614	6.885	.000
	Within Groups	1295417.468	51	25400.343		
	Total	2169780.537	56			
Pb	Between Groups	563.741	5	112.748	3.657	.007
	Within Groups	1572.552	51	30.834		
	Total	2136.293	56			
Ti	Between Groups	240323.265	5	48064.653	2.045	.088
	Within Groups	1198895.829	51	23507.761		
	Total	1439219.093	56			
Zn	Between Groups	222.133	5	44.427	.114	.989
	Within Groups	19840.754	51	389.034		
	Total	20062.887	56			
Na	Between Groups	3800.018	5	760.004	2.379	.051
	Within Groups	16295.527	51	319.520		
	Total	20095.545	56			
S	Between Groups	389135.839	5	77827.168	7.782	.000
	Within Groups	510061.038	51	10001.197		
	Total	899196.877	56			

Case Study 3: Statistical analysis of mean soil concentrations.

1: Topsoil; 2: Ditch; 3: Fill; 4: Layer; 5: Layer/Natural; 6: Natural

Element	Feature	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	2	33946.789	6246.695	4417.081	-22177.546	90071.124	29529.708	38363.870
	2	2	30438.592	1462.819	1034.369	17295.681	43581.503	29404.223	31472.962
	3	4	34051.727	1005.093	502.546	32452.399	35651.054	32893.672	35328.009
	4	8	34666.272	8312.864	2939.041	27716.543	41616.000	25550.114	53609.808
	5	3	27800.260	5259.287	3036.450	14735.466	40865.054	24747.697	33873.134
	6	3	28744.108	1893.359	1093.131	24040.742	33447.475	26807.776	30591.350
	Total	22	32360.952	6009.609	1281.252	29696.441	35025.464	24747.697	53609.808
Ca	1	2	7343.312	3558.656	2516.350	-24629.946	39316.570	4826.962	9859.662
	2	2	8403.262	141.845	100.300	7128.829	9677.694	8302.962	8503.562
	3	4	5424.687	786.675	393.337	4172.910	6676.463	4290.862	6100.662
	4	8	6587.1440	2163.8665	765.0423	4778.1063	8396.1816	4732.962	10668.918
	5	3	4748.0620	651.81628	376.3263	3128.8605	6367.2634	4351.962	5500.362
	6	3	5232.1286	1126.450	650.356	2433.871	8030.385	4374.562	6507.862
	Total	22	6174.073	1899.259	404.923	5331.989	7016.158	4290.862	10668.918
Cd	1	2	3.10700	.069296	.049000	2.48440	3.72960	3.058	3.156
	2	2	2.60100	.227688	.161000	.55530	4.64670	2.440	2.762
	3	4	2.68125	.175749	.087874	2.40159	2.96091	2.539	2.924
	4	8	3.12700	.665677	.235352	2.57048	3.68352	2.261	4.475
	5	3	2.65200	.059506	.034356	2.50418	2.79982	2.593	2.712
	6	3	2.71700	.526182	.303792	1.40989	4.02411	2.285	3.303
	Total	22	2.87564	.485606	.103531	2.66033	3.09094	2.261	4.475
Co	1	2	10.47450	2.653772	1.876500	-13.36869	34.31769	8.598	12.351
	2	2	10.39750	1.037326	.733500	1.07750	19.71750	9.664	11.131
	3	4	8.58450	.574499	.287250	7.67034	9.49866	7.924	9.153
	4	8	11.18563	2.053695	.726091	9.46869	12.90256	9.083	14.260
	5	3	11.35400	2.193930	1.266666	5.90398	16.80402	8.847	12.923
	6	3	10.73700	2.731502	1.577033	3.95157	17.52243	7.710	13.018
	Total	22	10.53818	1.999585	.426313	9.65162	11.42475	7.710	14.260
Cr	1	2	53.33950	10.132133	7.164500	-37.69410	144.37310	46.175	60.504
	2	2	39.61700	1.183697	.837000	28.98191	50.25209	38.780	40.454
	3	4	41.58100	1.102069	.551034	39.82736	43.33464	40.152	42.509
	4	8	50.74750	10.799243	3.818109	41.71911	59.77589	36.827	70.851
	5	3	45.84100	3.225608	1.862306	37.82815	53.85385	42.128	47.952
	6	3	42.25033	3.836991	2.215288	32.71872	51.78195	38.554	46.214
	Total	22	46.47686	8.335866	1.777213	42.78095	50.17278	36.827	70.851

Element	Feature	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Cu	1	2	41.36550	40.833295	28.87350	-325.50710	408.23810	12.492	70.239
	2	2	22.72500	5.437651	3.845000	-26.13036	71.58036	18.880	26.570
	3	4	12.05725	3.705903	1.852951	6.16033	17.95417	6.522	14.366
	4	8	25.24250	27.588901	9.754150	2.17760	48.30740	8.450	90.211
	5	3	13.73067	.817500	.471984	11.69988	15.76145	13.147	14.665
	6	3	12.21467	1.802005	1.040388	7.73824	16.69109	10.415	14.019
	Total	22	20.73573	20.426255	4.354892	11.67923	29.79222	6.522	90.211
Fe	1	2	20762.937	7794.905	5511.830	-49271.509	90797.384	15251.107	26274.768
	2	2	15205.780	2108.982	1491.276	-3742.678	34154.238	13714.504	16697.056
	3	4	15026.772	2987.670	1493.835	10272.722	19780.822	12055.543	18964.484
	4	8	21588.540	6776.130	2395.723	15923.553	27253.526	15555.681	32161.597
	5	3	20076.798	4640.758	2679.343	8548.516	31605.081	14718.123	22765.270
	6	3	20051.789	7976.254	4605.092	237.674	39865.903	11777.087	27691.656
	Total	22	19324.482	5935.977	1265.554	16692.617	21956.347	11777.087	32161.597
K	1	2	1362.450	166.6651	117.8500	-134.976	2859.876	1244.6	1480.3
	2	2	1252.600	44.1235	31.2000	856.166	1649.034	1221.4	1283.8
	3	4	1285.375	164.5946	82.2973	1023.468	1547.282	1055.5	1446.9
	4	8	1414.413	244.3299	86.3837	1210.148	1618.677	1045.9	1692.6
	5	3	1713.633	443.0392	255.7888	613.063	2814.204	1202.4	1985.5
	6	3	1415.133	285.0473	164.5721	707.037	2123.230	1115.7	1683.2
	Total	22	1412.418	265.1893	56.5385	1294.840	1529.997	1045.9	1985.5
Mg	1	2	6540.600	885.4391	626.1000	-1414.755	14495.955	5914.5	7166.7
	2	2	6615.100	15.2735	10.8000	6477.873	6752.327	6604.3	6625.9
	3	4	6747.650	640.2351	320.1176	5728.893	7766.407	5797.9	7193.7
	4	8	6545.600	691.6933	244.5505	5967.330	7123.870	5183.5	7354.3
	5	3	7795.767	948.0992	547.3853	5440.558	10150.976	6701.0	8345.7
	6	3	6850.100	1022.8852	590.5630	4309.112	9391.088	5670.4	7490.2
	Total	22	6800.200	785.8038	167.5339	6451.794	7148.606	5183.5	8345.7
Mn	1	2	180.228	26.919	19.035	-61.6346	422.09061	161.193	199.263
	2	2	123.29550	43.681521	30.8875	-269.16740	515.75840	92.408	154.183
	3	4	92.61375	11.941484	5.970742	73.61218	111.61532	79.914	108.753
	4	8	136.57488	25.636908	9.064016	115.14188	158.00787	81.508	169.493
	5	3	132.32967	25.655222	14.81205	68.59856	196.06077	102.723	148.013
	6	3	147.08633	82.493967	47.62791	-57.84004	352.01271	81.713	239.773
	Total	22	132.19768	40.500676	8.634773	114.24069	150.15468	79.914	239.773
Ni	1	2	30.79550	.850649	.601500	23.15272	38.43828	30.194	31.397
	2	2	28.16500	.589727	.417000	22.86651	33.46349	27.748	28.582
	3	4	23.89400	1.206388	.603194	21.97437	25.81363	22.189	24.917
	4	8	31.11113	3.496439	1.236178	28.18803	34.03422	26.597	35.761
	5	3	30.32367	5.073272	2.929055	17.72096	42.92637	24.468	33.398
	6	3	28.29700	4.688837	2.707101	16.64928	39.94472	22.949	31.702
	Total	22	29.01127	4.029519	.859096	27.22468	30.79786	22.189	35.761

Element	Feature	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
P	1	2	707.6050	66.84280	47.26500	107.0462	1308.1638	660.34	754.87
	2	2	710.7350	21.91324	15.49500	513.8524	907.6176	695.24	726.23
	3	4	552.9300	75.79160	37.89580	432.3286	673.5314	485.16	660.11
	4	8	586.4538	98.71905	34.90246	503.9226	668.9849	491.02	765.09
	5	3	428.9367	105.26933	60.77727	167.4332	690.4402	363.52	550.37
	6	3	549.0633	123.30955	71.19280	242.7454	855.3812	434.31	679.44
	Total	22	576.0923	116.28834	24.79276	524.5329	627.6516	363.52	765.09
Pb	1	2	20.14650	6.899241	4.878500	-41.84072	82.13372	15.268	25.025
	2	2	15.43100	.255973	.181000	13.13118	17.73082	15.250	15.612
	3	4	16.23450	6.076765	3.038382	6.56501	25.90399	11.859	24.902
	4	8	14.92350	4.312847	1.524822	11.31787	18.52913	7.337	20.190
	5	3	9.70667	2.326054	1.342948	3.92843	15.48491	8.100	12.374
	6	3	16.20500	7.902200	4.562337	-3.42515	35.83515	9.205	24.774
	Total	22	15.14618	5.218067	1.112496	12.83262	17.45974	7.337	25.025
Ti	1	2	187.65400	99.921259	70.65500	-710.10290	1085.4109	116.999	258.309
	2	2	154.47400	31.784450	22.47500	-131.09795	440.04595	131.999	176.949
	3	4	193.95150	25.452920	12.72646	153.45022	234.45278	161.819	223.609
	4	8	196.94525	42.623956	15.06984	161.31073	232.57977	125.449	249.579
	5	3	269.69567	100.47299	58.00811	20.10691	519.28442	153.849	333.049
	6	3	234.82567	88.881339	51.31566	14.03218	455.61915	137.899	312.509
	Total	22	206.78127	63.062867	13.44504	178.82076	234.74178	116.999	333.049
Zn	1	2	48.66250	15.762117	11.14550	-92.95450	190.27950	37.517	59.808
	2	2	86.50550	20.477105	14.47950	-97.47399	270.48499	72.026	100.985
	3	4	50.05925	2.278871	1.139436	46.43306	53.68544	46.947	51.853
	4	8	49.41613	9.847734	3.481700	41.18321	57.64904	34.810	60.924
	5	3	46.52900	1.815847	1.048380	42.01819	51.03981	44.460	47.858
	6	3	52.94033	9.829090	5.674828	28.52352	77.35715	41.690	59.863
	Total	22	52.92318	13.985895	2.981803	46.72218	59.12418	34.810	100.985
Na	1	2	118.07100	31.508678	22.28000	-165.02324	401.16524	95.791	140.351
	2	2	99.22100	2.800143	1.980000	74.06271	124.37929	97.241	101.201
	3	4	123.81350	9.935527	4.967763	108.00386	139.62314	115.251	134.261
	4	8	128.77350	16.911391	5.979080	114.63522	142.91178	107.841	157.811
	5	3	125.55767	5.094746	2.941453	112.90162	138.21372	121.981	131.391
	6	3	115.53767	21.674691	12.51388	61.69475	169.38058	91.421	133.391
	Total	22	121.96873	16.764925	3.574294	114.53558	129.40188	91.421	157.811
S	1	2	954.78400	810.77570	573.3050	-6329.7467	8239.3147	381.479	1528.089
	2	2	1534.2390	193.67654	136.9500	-205.87574	3274.3537	1397.289	1671.189
	3	4	600.39400	179.67701	89.83850	314.48777	886.30023	345.729	755.509
	4	8	826.10775	379.52357	134.1818	508.81810	1143.3974	285.539	1311.289
	5	3	260.43633	294.05338	169.7718	-470.03277	990.90544	89.975	599.979
	6	3	497.82900	477.21261	275.5188	-687.63285	1683.2908	157.929	1043.389
	Total	22	739.24000	477.36517	101.7745	527.58814	950.89186	89.975	1671.189

Case Study 3: Statistical analysis of variance of soil concentrations.
Significance level = 0.005

Element		Sum of Squares	df	Mean Square	F	Sig.
Al	Between Groups	168015958.292	5	33603191.658	.911	.499
	Within Groups	590407504.454	16	36900469.028		
	Total	758423462.746	21			
Ca	Between Groups	25046445.088	5	5009289.018	1.581	.222
	Within Groups	50704467.370	16	3169029.211		
	Total	75750912.458	21			
Cd	Between Groups	1.140	5	.228	.957	.472
	Within Groups	3.812	16	.238		
	Total	4.952	21			
Co	Between Groups	20.784	5	4.157	1.053	.422
	Within Groups	63.181	16	3.949		
	Total	83.965	21			
Cr	Between Groups	484.895	5	96.979	1.593	.219
	Within Groups	974.325	16	60.895		
	Total	1459.220	21			
Cu	Between Groups	1687.879	5	337.576	.764	.589
	Within Groups	7073.991	16	442.124		
	Total	8761.870	21			
Fe	Between Groups	156239494.159	5	31247898.832	.857	.531
	Within Groups	583713014.776	16	36482063.424		
	Total	739952508.935	21			
K	Between Groups	392882.858	5	78576.572	1.160	.371
	Within Groups	1083949.255	16	67746.828		
	Total	1476832.113	21			
Mg	Between Groups	3713852.623	5	742770.525	1.284	.319
	Within Groups	9253388.017	16	578336.751		
	Total	12967240.640	21			
Mn	Between Groups	11858.218	5	2371.644	1.680	.196
	Within Groups	22588.182	16	1411.761		
	Total	34446.400	21			
Mo	Between Groups	.049	5	.010	.620	.687
	Within Groups	.251	16	.016		
	Total	.299	21			
Ni	Between Groups	154.518	5	30.904	2.652	.063
	Within Groups	186.460	16	11.654		
	Total	340.978	21			
P	Between Groups	141009.376	5	28201.875	3.156	.036
	Within Groups	142973.164	16	8935.823		
	Total	283982.540	21			

<i>Element</i>		<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
Pb	Between Groups	147.431	5	29.486	1.112	.393
	Within Groups	424.361	16	26.523		
	Total	571.793	21			
Tl	Between Groups	21870.325	5	4374.065	1.135	.382
	Within Groups	61645.104	16	3852.819		
	Total	83515.429	21			
Zn	Between Groups	2545.713	5	509.143	5.215	.005
	Within Groups	1561.998	16	97.625		
	Total	4107.710	21			
Na	Between Groups	1612.072	5	322.414	1.202	.352
	Within Groups	4290.245	16	268.140		
	Total	5902.317	21			
S	Between Groups	2357042.813	5	471408.563	3.106	.038
	Within Groups	2428384.903	16	151774.056		
	Total	4785427.716	21			

Appendix 5 Statistical Analysis of Variations in Plant Chemical Concentrations

Statistical Analysis of Means for all Plant Samples from All Experimental Groups

1: Experiment 3 plants; 2: Experiment 5 plants; 3: Experiment 2 plants; 4: Experiment 4 plants

Element	Experimental group	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	44	753.9982	1052.07410	158.60614	434.1384	1073.8579	110.68	7026.98
	2	11	73.9248	37.11758	11.19137	48.9889	98.8607	25.51	136.59
	3	24	146.8067	82.95112	16.93233	111.7795	181.8339	47.53	439.73
	4	10	201.1340	164.90414	52.14727	83.1687	319.0993	81.13	645.65
	Total	89	444.0876	800.96694	84.90233	275.3620	612.8131	25.51	7026.98
Ca	1	44	2944.0282	537.12595	80.97478	2780.7270	3107.3294	1938.91	4284.61
	2	11	5312.6918	505.81053	152.50761	4972.8837	5652.5000	4453.71	5964.91
	3	24	4657.2100	482.76687	98.54437	4453.3554	4861.0646	3784.91	5731.71
	4	10	6046.6000	751.33097	237.59172	5509.1302	6584.0698	4842.61	7148.81
	Total	89	4047.3696	1285.74091	136.28826	3776.5253	4318.2138	1938.91	7148.81
Cr	1	44	2.141	2.1507	.3242	1.487	2.795	.8	15.1
	2	11	.365	.1878	.0566	.239	.492	.1	.6
	3	24	.666	.3315	.0677	.526	.806	.3	1.7
	4	10	1.145	.9382	.2967	.474	1.816	.4	3.7
	Total	89	1.412	1.7162	.1819	1.050	1.773	.1	15.1
Cu	1	44	4.83914	1.221299	.184118	4.46783	5.21045	2.356	8.260
	2	11	8.45064	1.698011	.511970	7.30990	9.59138	6.645	11.179
	3	24	4.56025	.648859	.132448	4.28626	4.83424	3.772	6.896
	4	10	10.65590	2.494109	.788706	8.87172	12.44008	7.707	15.520
	Total	89	5.86387	2.497428	.264727	5.33778	6.38995	2.356	15.520
Fe	1	44	558.85014	722.119548	108.86361	339.30573	778.39455	105.104	4847.414
	2	11	115.44236	54.260051	16.360021	78.98997	151.89476	42.909	199.324
	3	24	135.39708	68.849566	14.053859	106.32446	164.46971	62.214	399.284
	4	10	767.64900	966.869974	305.75113	75.99189	1459.3061	193.084	2800.414
	Total	89	413.31789	639.529638	67.790006	278.59950	548.03628	42.909	4847.414
K	1	44	24619.17405	3488.051641	525.84357	23558.709	25679.638	18274.499	32088.986
	2	11	48083.10555	11474.01365	3459.5452	40374.758	55791.452	31679.025	65966.025
	3	24	38668.68617	3045.808020	621.72295	37382.554	39954.818	32650.864	45681.151
	4	10	41470.02320	10253.68266	3242.4991	34134.980	48805.065	27464.100	58485.784
	Total	89	33201.19684	10701.16349	1134.3210	30946.972	35455.421	18274.499	65966.025
Mg	1	44	2369.257	316.0195	47.6417	2273.178	2465.336	1659.5	3320.2
	2	11	3869.627	457.5208	137.9477	3562.261	4176.994	3126.5	4478.9
	3	24	2288.437	233.6815	47.7000	2189.762	2387.113	1808.8	2698.8
	4	10	4825.740	470.5394	148.7976	4489.136	5162.344	4023.7	5370.0
	Total	89	2808.911	939.6261	99.6002	2610.977	3006.846	1659.5	5370.0

Element	Experimental group	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Mn	1	44	24.75277	11.217984	1.691175	21.34219	28.16335	10.341	68.516
	2	11	110.93018	20.266227	6.110497	97.31515	124.54522	71.700	140.860
	3	24	44.34921	16.052431	3.276689	37.57086	51.12756	17.008	77.408
	4	10	142.90900	43.208243	13.663646	111.99969	173.81831	102.240	213.830
	Total	89	53.96433	46.075542	4.883998	44.25841	63.67024	10.341	213.830
Pb	1	44	2219.739	671.5336	101.2375	2015.574	2423.904	1161.0	4189.7
	2	11	6431.536	971.6178	292.9538	5778.795	7084.278	5258.6	8052.5
	3	24	4619.254	424.7114	86.6938	4439.914	4798.594	3969.0	5893.4
	4	10	7349.672	1496.2622	473.1596	6279.310	8420.033	5394.9	10310.2
	Total	89	3963.755	2075.0291	219.9526	3526.646	4400.865	1161.0	10310.2
Zn	1	44	2095.1173	377.39790	56.89487	1980.3778	2209.8567	1426.99	3171.89
	2	11	2817.4718	592.93522	178.77669	2419.1325	3215.8111	1896.69	3690.49
	3	24	2340.3108	157.70243	32.19087	2273.7189	2406.9027	2072.29	2602.69
	4	10	3526.9100	984.60716	311.36012	2822.5645	4231.2555	2160.39	5133.29
	Total	89	2411.3922	654.68182	69.39613	2273.4820	2549.3025	1426.99	5133.29
Na	1	44	48.40177	53.654713	8.088752	32.08925	64.71430	9.184	364.960
	2	11	6.01518	8.622342	2.599734	.22261	11.80775	1.455	31.541
	3	24	10.90567	6.490396	1.324847	8.16501	13.64632	2.680	32.341
	4	10	8.20020	5.316912	1.681355	4.39671	12.00369	3.215	21.844
	Total	89	28.53464	42.679476	4.524015	19.54411	37.52517	1.455	364.960
S	1	44	15.55161	4.877216	.735268	14.06880	17.03442	8.327	32.469
	2	11	32.56691	11.302040	3.407693	24.97410	40.15972	18.801	45.595
	3	24	26.00363	6.036560	1.232208	23.45461	28.55264	17.928	38.323
	4	10	42.65760	13.336732	4.217445	33.11708	52.19812	24.356	66.618
	Total	89	23.51876	11.795496	1.250320	21.03402	26.00351	8.327	66.618

Statistical Analysis of Variance for all Plant Samples from All Experimental Groups

Significance level = 0.05.

Element		Sum of Squares	df	Mean Square	F	Sig.
Al	Between Groups	8444473.162	3	2814824.387	4.983	.003
	Within Groups	48011754.576	85	564844.171		
	Total	56456227.738	88			
Ca	Between Groups	120070333.464	3	40023444.488	133.910	.000
	Within Groups	25405079.751	85	298883.291		
	Total	145475413.214	88			

Element		Sum of Squares	df	Mean Square	F	Sig.
Cr	Between Groups	49.501	3	16.500	6.689	.000
	Within Groups	209.692	85	2.467		
	Total	259.193	88			
Cu	Between Groups	390.230	3	130.077	69.696	.000
	Within Groups	158.639	85	1.866		
	Total	548.869	88			
Fe	Between Groups	5017196.799	3	1672398.933	4.589	.005
	Within Groups	30974641.066	85	364407.542		
	Total	35991837.866	88			
K	Between Groups	7078009787.332	3	2359336595.77	66.863	.000
	Within Groups	2999301418.800	85	35285899.045		
	Total	10077311206.13	88			
Mg	Between Groups	68058740.399	3	22686246.800	200.113	.000
	Within Groups	9636218.450	85	113367.276		
	Total	77694958.849	88			
Mn	Between Groups	154572.411	3	51524.137	135.810	.000
	Within Groups	32247.678	85	379.384		
	Total	186820.089	88			
Pb	Between Groups	325776107.591	3	108592035.864	173.732	.000
	Within Groups	53129517.989	85	625053.153		
	Total	378905625.580	88			
Zn	Between Groups	18780280.800	3	6260093.600	28.098	.000
	Within Groups	18937248.879	85	222791.163		
	Total	37717529.680	88			
Na	Between Groups	34538.948	3	11512.983	7.782	.000
	Within Groups	125756.370	85	1479.487		
	Total	160295.317	88			
S	Between Groups	7504.619	3	2501.540	44.867	.000
	Within Groups	4739.149	85	55.755		
	Total	12243.768	88			

Statistical Analysis of Means of Concentrations from Experiment 2 Plant Samples

1: Exterior; 2: Outer ditch; 3: Outer ditch reverse anomaly/ bank; 4: Inter-ditch; 5: Inner ditch; 6: Inner ditch branch; 7: Interior

Element	Feature	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	1	149.330	.	.	.	.	149.33	149.33
	2	2	135.845	19.59393	13.85500	-40.1995	311.8895	121.99	149.70
	3	1	93.750	.	.	.	.	93.75	93.75
	4	7	105.997	59.44703	22.46887	51.0180	160.976	47.53	195.58
	5	4	231.402	154.15479	77.07740	-13.8922	476.697	114.32	439.73
	6	1	95.550	.	.	.	.	95.55	95.55
	7	8	155.681	51.79500	18.31230	112.3795	198.983	87.33	207.82
	Total	24	146.806	82.95112	16.93233	111.7795	181.833	47.53	439.73
Ca	1	1	4283.610	.	.	.	.	4283.61	4283.61
	2	2	4823.410	115.11698	81.40000	3789.124	5857.695	4742.01	4904.81
	3	1	4305.210	.	.	.	.	4305.21	4305.21
	4	7	4660.510	514.14030	194.32677	4185.0095	5136.010	4032.11	5298.11
	5	4	4908.110	551.26681	275.63341	4030.9215	5785.298	4594.91	5731.71
	6	1	4507.510	.	.	.	.	4507.51	4507.51
	7	8	4596.735	564.06896	199.42849	4125.1615	5068.308	3784.91	5188.41
	Total	24	4657.210	482.76687	98.54437	4453.3554	4861.0646	3784.91	5731.71
Cr	1	1	.66600	.	.	.	.	.666	.666
	2	2	.54550	.021920	.015500	.34855	.74245	.530	.561
	3	1	.26700	.	.	.	.	.267	.267
	4	7	.56129	.221504	.083721	.35643	.76614	.267	.917
	5	4	.90000	.567947	.283973	-.00373	1.80373	.362	1.669
	6	1	.85500	.	.	.	.	.855	.855
	7	8	.69613	.324831	.114845	.42456	.96769	.298	1.260
	Total	24	.66571	.331542	.067676	.52571	.80571	.267	1.669
Cu	1	1	4.5020	.	.	.	.	4.50	4.50
	2	2	4.0845	.01061	.00750	3.9892	4.1798	4.08	4.09
	3	1	4.2670	.	.	.	.	4.27	4.27
	4	7	4.3731	.41607	.15726	3.9883	4.7579	3.77	5.11
	5	4	5.2015	1.23532	.61766	3.2358	7.1672	4.11	6.90
	6	1	5.0690	.	.	.	.	5.07	5.07
	7	8	4.5026	.43903	.15522	4.1356	4.8697	4.08	5.19
	Total	24	4.5603	.64886	.13245	4.2863	4.8342	3.77	6.90

Element	Feature	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Fe	1	1	127.36400	.	.	.	.	127.364	127.364
	2	2	111.75400	11.384419	8.050000	9.46905	214.03895	103.704	119.804
	3	1	87.39700	.	.	.	.	87.397	87.397
	4	7	101.418	38.744	14.644	65.585	137.251	62.214	160.064
	5	4	218.434	129.389	64.694	12.546	424.321	123.534	399.284
	6	1	89.631	.	.	.	.	89.631	89.631
	7	8	142.245	33.903	11.986	113.901	170.588	102.524	177.934
	Total	24	135.39708	68.849566	14.0538	106.324	164.469	62.214	399.284
K	1	1	36784.599	.	.	.	.	36784.599	36784.599
	2	2	32943.382	413.682	292.518	29226.588	36660.175	32650.864	33235.900
	3	1	37158.019	.	.	.	.	37158.020	37158.020
	4	7	40717.881	3294.480	1245.196	37670.995	43764.768	35336.115	45681.151
	5	4	38939.390	1752.194	876.097	36151.258	41727.522	36678.411	40371.800
	6	1	41678.669	.	.	.	.	41678.669	41678.669
	7	8	38219.710	1968.182	695.857	36574.268	39865.151	34117.991	40406.109
	Total	24	38668.686	3045.808	621.722	37382.554	39954.818	32650.864	45681.151
Mg	1	1	2122.700	.	.	.	.	2122.7	2122.7
	2	2	2389.150	59.1848	41.8500	1857.395	2920.905	2347.3	2431.0
	3	1	2010.400	.	.	.	.	2010.4	2010.4
	4	7	2226.257	296.0726	111.9049	1952.436	2500.079	1808.8	2622.1
	5	4	2446.200	182.9292	91.4646	2155.119	2737.281	2284.7	2698.8
	6	1	2210.800	.	.	.	.	2210.8	2210.8
	7	8	2303.963	228.8104	80.8967	2112.672	2495.253	2003.6	2593.0
	Total	24	2288.438	233.6815	47.7000	2189.762	2387.113	1808.8	2698.8
Mn	1	1	56.56200	.	.	.	.	56.562	56.562
	2	2	17.31700	.436992	.309000	13.39078	21.24322	17.008	17.626
	3	1	50.99600	.	.	.	.	50.996	50.996
	4	7	41.20771	12.845554	4.855163	29.32756	53.08787	27.356	63.170
	5	4	48.36675	12.994562	6.497281	27.68950	69.04400	29.118	57.654
	6	1	51.77000	.	.	.	.	51.770	51.770
	7	8	48.56225	18.686556	6.606695	32.93990	64.18460	21.210	77.408
	Total	24	44.34921	16.052431	3.276689	37.57086	51.12756	17.008	77.408
Pb	1	1	4334.300	.	.	.	.	4334.3	4334.3
	2	2	4005.650	51.8309	36.6500	3539.968	4471.332	3969.0	4042.3
	3	1	4317.900	.	.	.	.	4317.9	4317.9
	4	7	4670.629	588.8631	222.5693	4126.021	5215.236	4142.3	5893.4
	5	4	4780.275	273.6076	136.8038	4344.904	5215.646	4493.4	5141.1
	6	1	4722.800	.	.	.	.	4722.8	4722.8
	7	8	4707.538	320.8500	113.4376	4439.300	4975.775	4313.0	5119.3
	Total	24	4619.254	424.7114	86.6938	4439.914	4798.594	3969.0	5893.4

Element	Feature	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Zn	1	1	2317.5900	.	.	.	.	2317.59	2317.59
	2	2	2104.4400	45.46697	32.15000	1695.935	2512.944	2072.29	2136.59
	3	1	2278.8900	.	.	.	.	2278.89	2278.89
	4	7	2434.1043	159.39472	60.24554	2286.688	2581.519	2106.49	2591.79
	5	4	2354.1150	154.27109	77.13554	2108.635	2599.594	2199.49	2550.99
	6	1	2430.8900	.	.	.	.	2430.89	2430.89
	7	8	2309.5025	147.55429	52.16832	2186.144	2432.861	2150.29	2602.69
	Total	24	2340.3108	157.70243	32.19087	2273.718	2406.902	2072.29	2602.69
Na	1	1	10.1760	.	.	.	.	10.18	10.18
	2	2	11.0530	1.39441	.98600	-1.4753	23.581	10.07	12.04
	3	1	6.8810	.	.	.	.	6.88	6.88
	4	7	7.8223	5.02666	1.89990	3.1734	12.471	2.68	16.13
	5	4	16.7188	11.64249	5.82124	-1.8070	35.244	6.48	32.34
	6	1	5.0010	.	.	.	.	5.00	5.00
	7	8	11.9926	4.56509	1.61400	8.1761	15.809	6.36	19.93
	Total	24	10.9057	6.49040	1.32485	8.1650	13.646	2.68	32.34
S	1	1	20.0870	.	.	.	.	20.09	20.09
	2	2	20.7740	4.02485	2.84600	-15.3879	56.935	17.93	23.62
	3	1	22.9240	.	.	.	.	22.92	22.92
	4	7	22.6701	3.64675	1.37834	19.2975	26.042	18.61	28.71
	5	4	28.1398	3.50296	1.75148	22.5658	33.713	25.11	32.31
	6	1	25.9580	.	.	.	.	25.96	25.96
	7	8	30.2900	7.20223	2.54637	24.2688	36.311	18.28	38.32
	Total	24	26.0036	6.03656	1.23221	23.4546	28.552	17.93	38.32

Statistical Analysis of Variance of Concentrations from Experiment 2 Plant Samples

<i>Element</i>		<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
Al	Between Groups	46602.664	6	7767.111	1.183	.361
	Within Groups	111657.774	17	6568.104		
	Total	158260.438	23			
Ca	Between Groups	622273.205	6	103712.201	.372	.887
	Within Groups	4738195.255	17	278717.368		
	Total	5360468.460	23			
Cr	Between Groups	.527	6	.088	.746	.621
	Within Groups	2.001	17	.118		
	Total	2.528	23			
Cu	Between Groups	2.717	6	.453	1.105	.399
	Within Groups	6.966	17	.410		
	Total	9.683	23			
Fe	Between Groups	41618.400	6	6936.400	1.749	.170
	Within Groups	67407.644	17	3965.156		
	Total	109026.044	23			
K	Between Groups	111750287.615	6	18625047.936	3.116	.030
	Within Groups	101619481.698	17	5977616.570		
	Total	213369769.314	23			
Mg	Between Groups	259636.375	6	43272.729	.738	.626
	Within Groups	996325.621	17	58607.389		
	Total	1255961.996	23			
Mn	Between Groups	1985.524	6	330.921	1.427	.261
	Within Groups	3941.128	17	231.831		
	Total	5926.652	23			
Pb	Between Groups	1120292.814	6	186715.469	1.048	.430
	Within Groups	3028441.486	17	178143.617		
	Total	4148734.300	23			
Zn	Between Groups	193699.370	6	32283.228	1.451	.253
	Within Groups	378311.910	17	22253.642		
	Total	572011.280	23			
Na	Between Groups	262.809	6	43.802	1.055	.426
	Within Groups	706.071	17	41.534		
	Total	968.881	23			
S	Between Groups	342.212	6	57.035	1.955	.129
	Within Groups	495.910	17	29.171		
	Total	838.121	23			

*Experiment 3: Statistical Analysis of Plant Concentrations by Archaeological Feature**1: Topsoil; 2: Bank; 3: Medial ditch; 4: Internal ditch; 5: Natural*

Element	Feature	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	10	271.9840	124.07341	39.23546	183.2272	360.7408	110.68	493.96
	2	3	1187.3067	660.05236	381.08141	-452.3543	2826.9676	454.36	1734.78
	3	12	496.7975	178.41363	51.50358	383.4389	610.1561	256.68	903.59
	4	6	491.2300	190.80225	77.89469	290.9953	691.4647	312.84	746.61
	5	13	1383.477	1751.356	485.738	325.143	2441.811	463.26	7026.98
	Total	44	753.998	1052.074	158.606	434.138	1073.857	110.68	7026.98
Ca	1	10	3582.1600	336.13267	106.29448	3341.7052	3822.6148	3200.51	4284.61
	2	3	3151.9433	505.32871	291.75167	1896.6372	4407.2494	2697.81	3696.31
	3	12	2818.4433	401.31136	115.84861	2563.4623	3073.4244	2321.61	3785.81
	4	6	2689.2267	365.82004	149.34541	2305.3221	3073.1313	2254.71	3229.81
	5	13	2638.7023	451.37777	125.18967	2365.9374	2911.4672	1938.91	3550.71
	Total	44	2944.0282	537.12595	80.97478	2780.7270	3107.3294	1938.91	4284.61
Cr	1	10	1.38210	.571890	.180848	.97299	1.79121	.817	2.511
	2	3	2.42267	1.140956	.658731	-.41163	5.25696	1.348	3.620
	3	12	1.65025	.570076	.164567	1.28804	2.01246	.767	2.400
	4	6	1.53633	.724076	.295603	.77646	2.29620	.794	2.736
	5	13	3.39115	3.602634	.999191	1.21410	5.56820	1.437	15.054
	Total	44	2.14080	2.150660	.324224	1.48694	2.79466	.767	15.054
Cu	1	10	4.06740	.991864	.313655	3.35786	4.77694	2.356	5.389
	2	3	6.07067	1.237738	.714608	2.99596	9.14538	5.313	7.499
	3	12	4.79117	.716811	.206925	4.33573	5.24661	3.325	6.244
	4	6	4.41367	.878886	.358804	3.49133	5.33600	2.985	5.609
	5	13	5.38923	1.504211	.417193	4.48025	6.29822	3.822	8.260
	Total	44	4.83914	1.221299	.184118	4.46783	5.21045	2.356	8.260
Fe	1	10	240.131	126.689	40.062	149.502	330.759	105.104	522.064
	2	3	777.934	420.775	242.935	-267.331	1823.19938	326.604	1159.414
	3	12	381.889	109.412	31.584	312.372	451.40697	269.764	555.644
	4	6	324.369	124.427	50.797393	193.790	454.94786	205.024	535.274
	5	13	1025.030	1191.088	330.348	305.263	1744.798	336.134	4847.414
	Total	44	558.850	722.119	108.863	339.305	778.394	105.104	4847.414
K	1	10	23403.477	2936.738	928.678	21302.661	25504.293	20067.702	28383.239
	2	3	24414.145	2675.825	1544.888	17767.027	31061.263	21372.308	26404.595
	3	12	25830.062	2924.925	844.353	23971.653	27688.471	19710.689	28537.052
	4	6	23826.411	2904.807	1185.882	20778.002	26874.820	21047.518	28668.771
	5	13	24849.786	4636.454	1285.921	22048.005	27651.568	18274.499	32088.986
	Total	44	24619.174	3488.051	525.843	23558.709	25679.638	18274.499	32088.986

Element	Feature	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Mg	1	10	2710.970	285.724	90.354	2506.575	2915.365	2345.9	3320.2
	2	3	2448.700	258.7942	149.4149	1805.820	3091.580	2153.7	2637.5
	3	12	2316.975	232.4222	67.0945	2169.301	2464.649	1787.8	2688.1
	4	6	2120.150	86.3388	35.2477	2029.543	2210.757	1991.6	2220.0
	5	13	2251.300	291.7661	80.9214	2074.988	2427.612	1659.5	2845.1
	Total	44	2369.257	316.0195	47.6417	2273.178	2465.336	1659.5	3320.2
Mn	1	10	16.12370	4.723750	1.493781	12.74453	19.50287	10.341	23.043
	2	3	39.46700	2.928738	1.690908	32.19161	46.74239	36.204	41.868
	3	12	20.66925	4.486305	1.295085	17.81879	23.51971	14.034	29.111
	4	6	19.31967	2.520699	1.029071	16.67436	21.96498	15.366	23.327
	5	13	34.27192	12.880147	3.572310	26.48853	42.05532	21.537	68.516
	Total	44	24.75277	11.217984	1.691175	21.34219	28.16335	10.341	68.516
Pb	1	10	2616.770	605.7080	191.5417	2183.473	3050.067	2110.3	4189.7
	2	3	1883.467	220.0093	127.0224	1336.933	2430.000	1699.8	2127.3
	3	12	2156.675	582.6145	168.1863	1786.499	2526.851	1330.5	3175.3
	4	6	2001.150	615.5117	251.2816	1355.210	2647.090	1161.0	2862.2
	5	13	2151.031	819.1944	227.2037	1655.997	2646.065	1379.1	3880.8
	Total	44	2219.739	671.5336	101.2375	2015.574	2423.904	1161.0	4189.7
Zn	1	10	2190.2500	464.78252	146.97714	1857.7646	2522.7354	1426.99	2732.59
	2	3	2562.3900	628.49106	362.85948	1001.1317	4123.6483	1916.49	3171.89
	3	12	2122.2400	201.74844	58.23976	1994.0552	2250.4248	1709.99	2404.59
	4	6	2085.6567	320.52974	130.85572	1749.2813	2422.0320	1589.59	2496.89
	5	13	1893.4362	308.91571	85.67780	1706.7603	2080.1121	1530.89	2491.59
	Total	44	2095.1173	377.39790	56.89487	1980.3778	2209.8567	1426.99	3171.89
Na	1	10	21.5431	9.85454	3.11628	14.4936	28.5926	9.18	37.44
	2	3	60.8433	30.55037	17.63826	-15.0480	136.7347	27.28	87.02
	3	12	34.9081	11.14936	3.21854	27.8241	41.9920	18.59	55.43
	4	6	37.6362	14.04824	5.73517	22.8934	52.3789	25.39	55.41
	5	13	83.6156	87.56712	24.28675	30.6993	136.5319	32.19	364.96
	Total	44	48.4018	53.65471	8.08875	32.0892	64.7143	9.18	364.96
S	1	10	17.53540	6.238419	1.972761	13.07270	21.99810	12.063	32.469
	2	3	16.05000	2.946766	1.701316	8.72983	23.37017	13.364	19.202
	3	12	14.84258	3.574952	1.032000	12.57117	17.11400	9.513	21.439
	4	6	12.28200	1.284507	.524398	10.93399	13.63001	10.680	14.333
	5	13	16.07415	5.719606	1.586333	12.61783	19.53048	8.327	25.631
	Total	44	15.55161	4.877216	.735268	14.06880	17.03442	8.327	32.469

*Experiment 3: Statistical Analysis of Variance**Significance level = 0.005.*

Element		Sum of Squares	df	Mean Square	F	Sig.
Al	Between Groups	9245932.340	4	2311483.085	2.351	.071
	Within Groups	38349044.263	39	983308.827		
	Total	47594976.604	43			
Ca	Between Groups	5992520.390	4	1498130.097	9.110	.000
	Within Groups	6413163.916	39	164440.100		
	Total	12405684.305	43			
Cr	Between Groups	31.399	4	7.850	1.828	.143
	Within Groups	167.491	39	4.295		
	Total	198.890	43			
Cu	Between Groups	15.553	4	3.888	3.121	.025
	Within Groups	48.584	39	1.246		
	Total	64.138	43			
Fe	Between Groups	4690698.740	4	1172674.685	2.579	.052
	Within Groups	17731936.831	39	454665.047		
	Total	22422635.570	43			
K	Between Groups	36962499.225	4	9240624.806	.741	.570
	Within Groups	486197183.579	39	12466594.451		
	Total	523159682.804	43			
Mg	Between Groups	1772618.089	4	443154.522	6.854	.000
	Within Groups	2521719.199	39	64659.467		
	Total	4294337.288	43			
Mn	Between Groups	2949.333	4	737.333	11.680	.000
	Within Groups	2461.923	39	63.126		
	Total	5411.256	43			
Pb	Between Groups	2311355.791	4	577838.948	1.319	.280
	Within Groups	17079811.553	39	437943.886		
	Total	19391167.344	43			
Zn	Between Groups	1283677.048	4	320919.262	2.586	.052
	Within Groups	4840777.460	39	124122.499		
	Total	6124454.507	43			
Na	Between Groups	26678.797	4	6669.699	2.679	.046
	Within Groups	97110.818	39	2490.021		
	Total	123789.615	43			
S	Between Groups	113.824	4	28.456	1.221	.318
	Within Groups	909.027	39	23.308		
	Total	1022.851	43			

Experiment 3: Statistical Analysis of Mean Concentrations Based on Watering Regime*1: Optimally watered plants; 2: Waterlogged plants; 3: Droughted plants*

Element	Watering regime	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	17	523.375	340.833	82.664	348.135	698.616	140.43	1534.68
	2	13	1212.550	1782.601	494.404	135.335	2289.766	164.50	7026.98
	3	14	608.240	531.265	141.986	301.496	914.984	110.68	1882.68
	Total	44	753.998	1052.074	158.606	434.138	1073.857	110.68	7026.98
Ca	1	17	2943.780	462.464	112.164	2706.003	3181.557	1938.91	3771.11
	2	13	3144.2100	487.4266	135.187	2849.661	3438.759	2079.71	3901.01
	3	14	2758.4457	628.158	167.882	2395.757	3121.133	2176.91	4284.61
	Total	44	2944.0282	537.125	80.974	2780.727	3107.329	1938.91	4284.61
Cr	1	17	1.555	.8329	.2020	1.127	1.984	.8	3.4
	2	13	3.101	3.6338	1.0078	.905	5.297	.9	15.1
	3	14	1.960	.9228	.2466	1.427	2.493	1.1	4.1
	Total	44	2.141	2.1507	.3242	1.487	2.795	.8	15.1
Cu	1	17	4.78824	.744986	.180686	4.40520	5.17127	3.193	6.623
	2	13	5.41223	1.430387	.396718	4.54786	6.27661	3.071	8.260
	3	14	4.36879	1.338610	.357759	3.59590	5.14168	2.356	7.499
	Total	44	4.83914	1.221299	.184118	4.46783	5.21045	2.356	8.260
Fe	1	17	391.095	233.767	56.697	270.902	511.287	131.044	932.494
	2	13	871.12323	1227.178	340.358	129.546	1612.699	131.184	4847.414
	3	14	472.584	353.703	94.531	268.362	676.807	105.104	1302.714
	Total	44	558.850	722.119	108.863	339.305	778.394	105.104	4847.414
K	1	17	25626.445	3378.397	819.381	23889.434	27363.457	18274.499	32018.785
	2	13	24208.946	3579.530	992.783	22045.857	26372.034	19620.865	30070.920
	3	14	23776.984	3479.835	930.025	21767.787	25786.181	19710.689	32088.986
	Total	44	24619.174	3488.051	525.843	23558.709	25679.638	18274.499	32088.986
Mg	1	17	2417.794	298.8361	72.4784	2264.147	2571.441	1659.5	2928.2
	2	13	2368.654	231.9240	64.3241	2228.504	2508.804	2050.4	2845.1
	3	14	2310.879	404.9936	108.2391	2077.042	2544.715	1787.8	3320.2
	Total	44	2369.257	316.0195	47.6417	2273.178	2465.336	1659.5	3320.2
Mn	1	17	22.240	8.988	2.180	17.618	26.861	10.341	42.235
	2	13	25.962	14.724	4.083	17.064	34.860	11.267	68.516
	3	14	26.680	10.147	2.7119	20.821	32.539	16.354	51.472
	Total	44	24.752	11.217	1.691	21.342	28.163	10.341	68.516
Pb	1	17	2325.835	547.1284	132.6981	2044.528	2607.143	1379.4	3642.9
	2	13	2595.438	792.7056	219.8570	2116.411	3074.466	1660.7	4189.7
	3	14	1742.043	376.2126	100.5471	1524.824	1959.262	1161.0	2278.4
	Total	44	2219.739	671.5336	101.2375	2015.574	2423.904	1161.0	4189.7
Zn	1	17	2168.748	381.671	92.568	1972.511	2364.986	1530.89	3171.89
	2	13	1728.343	149.441	41.447	1638.037	1818.650	1426.99	1973.99
	3	14	2346.282	248.309	66.363	2202.913	2489.652	1796.89	2732.59
	Total	44	2095.117	377.397	56.894	1980.377	2209.856	1426.99	3171.89

Element	Watering regime	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Na	1	17	36.464	21.517	5.218	25.401	47.527	9.813	89.013
	2	13	73.215	89.552	24.837	19.098	127.331	12.111	364.960
	3	14	39.855	25.864	6.912	24.921	54.789	9.184	102.290
	Total	44	48.401	53.654	8.088	32.089	64.714	9.184	364.960
S	1	17	14.755	4.668	1.132	12.355	17.155	9.387	25.631
	2	13	17.839	5.658	1.569	14.420	21.258	11.995	32.469
	3	14	14.393	3.847	1.028	12.172	16.615	8.327	21.273
	Total	44	15.551	4.877	.7352	14.068	17.034	8.327	32.469

Experiment 3: Statistical Analysis of Variance.

Significance level = 0.005.

Element		Sum of Squares	df	Mean Square	F	Sig.
Al	Between Groups	3935122.496	2	1967561.248	1.848	.170
	Within Groups	43659854.107	41	1064874.490		
	Total	47594976.604	43			
Ca	Between Groups	1003118.858	2	501559.429	1.803	.178
	Within Groups	11402565.447	41	278111.352		
	Total	12405684.305	43			
Cr	Between Groups	18.268	2	9.134	2.073	.139
	Within Groups	180.621	41	4.405		
	Total	198.890	43			
Cu	Between Groups	7.411	2	3.705	2.678	.081
	Within Groups	56.727	41	1.384		
	Total	64.138	43			
Fe	Between Groups	1850281.786	2	925140.893	1.844	.171
	Within Groups	20572353.784	41	501764.726		
	Total	22422635.570	43			
K	Between Groups	29365829.397	2	14682914.698	1.219	.306
	Within Groups	493793853.407	41	12043752.522		
	Total	523159682.804	43			
Mg	Between Groups	87766.783	2	43883.391	.428	.655
	Within Groups	4206570.505	41	102599.281		
	Total	4294337.288	43			
Mn	Between Groups	178.346	2	89.173	.699	.503
	Within Groups	5232.910	41	127.632		
	Total	5411.256	43			

Element		Sum of Squares	df	Mean Square	F	Sig.
Pb	Between Groups	5221020.780	2	2610510.390	7.553	.002
	Within Groups	14170146.564	41	345613.331		
	Total	19391167.344	43			
Zn	Between Groups	2724141.105	2	1362070.552	16.423	.000
	Within Groups	3400313.403	41	82934.473		
	Total	6124454.507	43			
Na	Between Groups	11448.862	2	5724.431	2.089	.137
	Within Groups	112340.753	41	2740.018		
	Total	123789.615	43			
S	Between Groups	97.572	2	48.786	2.162	.128
	Within Groups	925.279	41	22.568		
	Total	1022.851	43			

Experiment 4: Statistical Analysis of Means. Concentrations Following Initial Watering Regime

1: Optimally watered plants; 2: Waterlogged plants; 3: Droughted plants

Element	Watering regime	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	4	303.3425	232.92043	116.46022	-67.2859	673.9709	125.23	645.65
	2	3	165.6100	50.44417	29.12395	40.2997	290.9203	113.36	214.03
	3	3	100.3800	20.84579	12.03532	48.5962	152.1638	81.13	122.52
	Total	10	201.1340	164.90414	52.14727	83.1687	319.0993	81.13	645.65
Ca	1	4	5845.9350	978.29370	489.14685	4289.2514	7402.6186	4842.61	7148.81
	2	3	6492.5433	635.45545	366.88037	4913.9845	8071.1022	5850.51	7121.21
	3	3	5868.2100	523.72228	302.37120	4567.2117	7169.2083	5525.91	6471.11
	Total	10	6046.6000	751.33097	237.59172	5509.1302	6584.0698	4842.61	7148.81
Cd	1	4	.196250	.1385265	.0692632	-.024177	.416677	.0165	.3235
	2	3	-.039167	.0959184	.0553785	-.277441	.199108	-.1155	.0685
	3	3	.156167	.0894893	.0516667	-.066137	.378470	.1045	.2595
	Total	10	.113600	.1471050	.0465187	.008367	.218833	-.1155	.3235
Cr	1	4	1.66725	1.380822	.690411	-.52995	3.86445	.596	3.692
	2	3	.96767	.235918	.136207	.38161	1.55372	.811	1.239
	3	3	.62533	.217468	.125555	.08511	1.16555	.397	.830
	Total	10	1.14480	.938166	.296674	.47368	1.81592	.397	3.692
Cu	1	4	10.32950	1.152158	.576079	8.49616	12.16284	8.627	11.129
	2	3	8.28433	.527456	.304527	6.97406	9.59461	7.707	8.741
	3	3	13.46267	2.292753	1.323721	7.76715	19.15818	10.991	15.520
	Total	10	10.65590	2.494109	.788706	8.87172	12.44008	7.707	15.520

Element	Watering regime	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Fe	1	4	1462.154	1311.255	655.627	-624.346	3548.654	247.944	2800.414
	2	3	313.350	85.590	49.415	100.732	525.968	222.294	392.154
	3	3	295.940	111.074	64.129	20.015	571.865	193.084	413.724
	Total	10	767.649	966.869	305.751	75.991	1459.306	193.084	2800.414
K	1	4	42082.189	763.371	381.685	40867.494	43296.884	41030.992	42852.953
	2	3	28904.766	2178.245	1257.610	23493.704	34315.828	27464.100	31410.629
	3	3	53219.057	4781.679	2760.703	41340.707	65097.407	49150.197	58485.784
	Total	10	41470.023	10253.682	3242.499	34134.980	48805.065	27464.100	58485.784
Mg	1	4	4533.900	494.3063	247.1532	3747.348	5320.452	4023.7	5195.7
	2	3	4995.300	294.4155	169.9809	4263.931	5726.669	4813.9	5335.0
	3	3	5045.300	507.3141	292.8980	3785.062	6305.538	4460.7	5370.0
	Total	10	4825.740	470.5394	148.7976	4489.136	5162.344	4023.7	5370.0
Mn	1	4	132.1350	54.52298	27.26149	45.3768	218.8932	102.24	213.83
	2	3	183.2300	16.12008	9.30693	143.1855	223.2745	167.08	199.32
	3	3	116.9533	.95772	.55294	114.5742	119.3324	116.04	117.95
	Total	10	142.9090	43.20824	13.66365	111.9997	173.8183	102.24	213.83
Pb	1	4	6559.775	988.1766	494.0883	4987.365	8132.185	5394.9	7550.6
	2	3	6772.033	255.8924	147.7395	6136.361	7407.705	6568.8	7059.4
	3	3	8980.506	1675.2850	967.2262	4818.867	13142.144	7098.9	10310.2
	Total	10	7349.672	1496.2622	473.1596	6279.310	8420.033	5394.9	10310.2
Zn	1	4	3815.9900	602.49997	301.24998	2857.2781	4774.7019	3303.99	4640.19
	2	3	2332.9233	152.82743	88.23496	1953.2790	2712.5677	2160.39	2451.29
	3	3	4335.4567	713.09385	411.70493	2564.0333	6106.8800	3760.19	5133.29
	Total	10	3526.9100	984.60716	311.36012	2822.5645	4231.2555	2160.39	5133.29
Na	1	4	11.50675	7.133898	3.566949	.15513	22.85837	5.596	21.844
	2	3	7.17867	2.800499	1.616869	.22184	14.13549	4.123	9.623
	3	3	4.81300	1.545938	.892548	.97268	8.65332	3.215	6.301
	Total	10	8.20020	5.316912	1.681355	4.39671	12.00369	3.215	21.844
S	1	4	42.72750	8.027649	4.013824	29.95372	55.50128	37.022	54.614
	2	3	29.15900	6.969768	4.023997	11.84514	46.47286	24.356	37.153
	3	3	56.06300	10.596238	6.117741	29.74049	82.38551	45.426	66.618
	Total	10	42.65760	13.336732	4.217445	33.11708	52.19812	24.356	66.618

Experiment 4: Statistical Analysis of Variance. Concentrations Following Initial Watering regime.**Significance level = 0.005.**

Element		Sum of Squares	df	Mean Square	F	Sig.
Al	Between Groups	76026.279	2	38013.140	1.577	.272
	Within Groups	168714.109	7	24102.016		
	Total	244740.388	9			
Ca	Between Groups	853131.115	2	426565.557	.706	.525
	Within Groups	4227352.974	7	603907.568		
	Total	5080484.089	9			
Cd	Between Groups	.103	2	.051	3.910	.072
	Within Groups	.092	7	.013		
	Total	.195	9			
Cr	Between Groups	1.995	2	.998	1.179	.362
	Within Groups	5.926	7	.847		
	Total	7.921	9			
Cu	Between Groups	40.933	2	20.466	9.518	.010
	Within Groups	15.052	7	2.150		
	Total	55.985	9			
Fe	Between Groups	3216035.962	2	1608017.981	2.166	.185
	Within Groups	5197501.958	7	742500.280		
	Total	8413537.921	9			
K	Between Groups	889275439.482	2	444637719.74 1	54.637	.000
	Within Groups	56966633.529	7	8138090.504		
	Total	946242073.011	9			
Mg	Between Groups	571553.904	2	285776.952	1.408	.306
	Within Groups	1421112.440	7	203016.063		
	Total	1992666.344	9			
Mn	Between Groups	7362.755	2	3681.378	2.730	.133
	Within Groups	9439.815	7	1348.545		
	Total	16802.570	9			
Pb	Between Groups	11475603.715	2	5737801.858	4.631	.052
	Within Groups	8673600.424	7	1239085.775		
	Total	20149204.139	9			
Ti	Between Groups	2.673	2	1.336	1.450	.297
	Within Groups	6.451	7	.922		
	Total	9.123	9			
Zn	Between Groups	6572324.603	2	3286162.301	10.686	.007
	Within Groups	2152736.773	7	307533.825		
	Total	8725061.376	9			

Element		Sum of Squares	df	Mean Square	F	Sig.
Na	Between Groups	81.283	2	40.642	1.643	.260
	Within Groups	173.143	7	24.735		
	Total	254.426	9			
S	Between Groups	1085.770	2	542.885	7.378	.019
	Within Groups	515.045	7	73.578		
	Total	1600.816	9			

Experiment 4: Statistical Analysis of Means. Concentrations Following Final Watering Regime

1: Optimally watered plants; 2: Waterlogged plants; 3: Droughted plants

Element	Watering regime	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	3	327.4000	279.38471	161.3028	-366.6301	1021.4301	122.52	645.65
	2	4	159.2450	73.64937	36.82468	42.0524	276.4376	81.13	234.98
	3	3	130.7200	36.28782	20.95078	40.5761	220.8639	97.49	169.44
	Total	10	201.1340	164.90414	52.14727	83.1687	319.0993	81.13	645.65
Ca	1	3	6393.5433	817.26422	471.8477	4363.3465	8423.7402	5525.91	7148.81
	2	4	6030.2850	755.91375	377.9568	4827.4575	7233.1125	5449.01	7121.21
	3	3	5721.4100	821.89000	474.5184	3679.7221	7763.0979	4842.61	6471.11
	Total	10	6046.6000	751.33097	237.5917	5509.1302	6584.0698	4842.61	7148.81
Cd	1	3	.063167	.0442418	.0255430	-.046736	.173069	.0165	.1045
	2	4	.129500	.1625033	.0812517	-.129079	.388079	-.0705	.3235
	3	3	.142833	.2240722	.1293681	-.413793	.699459	-.1155	.2845
	Total	10	.113600	.1471050	.0465187	.008367	.218833	-.1155	.3235
Cr	1	3	1.92033	1.547877	.893667	-1.92481	5.76547	.830	3.692
	2	4	.90775	.383840	.191920	.29698	1.51852	.397	1.286
	3	3	.68533	.112010	.064669	.40708	.96358	.596	.811
	Total	10	1.14480	.938166	.296674	.47368	1.81592	.397	3.692
Cu	1	3	11.72600	3.461152	1.998297	3.12802	20.32398	8.741	15.520
	2	4	11.01400	2.247446	1.123723	7.43781	14.59019	8.405	13.877
	3	3	9.10833	1.694085	.978081	4.89999	13.31667	7.707	10.991
	Total	10	10.65590	2.494109	.788706	8.87172	12.44008	7.707	15.520
Fe	1	3	338.16067	127.00136	73.32427	22.67179	653.64954	193.084	429.244
	2	4	1418.6840	1359.1360	679.5680	744.00473	3581.3727	222.294	2800.414
	3	3	329.09067	82.944980	47.88830	123.04391	535.13742	247.944	413.724
	Total	10	767.64900	966.86997	305.7511	75.99189	1459.3061	193.084	2800.414

Element	Watering regime	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
K	1	3	40172.094	12301.055	7102.017	9614.5784	70729.610	27464.10	52021.192
	2	4	41251.410	7328.6486	3664.324	29589.894	52912.925	31410.6290	49150.197
	3	3	43059.436	15324.149	8847.402	4992.1374	81126.734	27839.5710	58485.784
	Total	10	41470.023	10253.682	3242.499	34134.980	48805.065	27464.1000	58485.784
Mg	1	3	5134.233	271.7644	156.9032	4459.133	5809.333	4837.0	5370.0
	2	4	4677.975	446.7744	223.3872	3967.057	5388.893	4350.3	5335.0
	3	3	4714.267	646.5336	373.2763	3108.188	6320.345	4023.7	5305.2
	Total	10	4825.740	470.5394	148.7976	4489.136	5162.344	4023.7	5370.0
Mn	1	3	171.0533	50.03022	28.88496	46.7714	295.3353	116.04	213.83
	2	4	132.4350	44.96354	22.48177	60.8880	203.9820	104.13	199.32
	3	3	128.7300	34.00810	19.63459	44.2492	213.2108	102.24	167.08
	Total	10	142.9090	43.20824	13.66365	111.9997	173.8183	102.24	213.83
Pb	1	3	7702.806	2276.4777	1314.325	2047.721	13357.890	6110.3	10310.2
	2	4	7708.775	1281.4438	640.7219	5669.712	9747.838	6568.8	9532.4
	3	3	6517.733	972.6027	561.5325	4101.654	8933.812	5394.9	7098.9
	Total	10	7349.672	1496.2622	473.1596	6279.310	8420.033	5394.9	10310.2
Ti	1	3	1.196833	1.8744803	1.082231	-3.459634	5.853300	-.1225	3.3425
	2	4	1.191500	.5569422	.2784711	.305281	2.077719	.5415	1.8145
	3	3	1.063500	.7516123	.4339435	-.803608	2.930608	.5385	1.9245
	Total	10	1.154700	1.0068346	.3183891	.434454	1.874946	-.1225	3.3425
Zn	1	3	4053.5233	1464.0822	845.2883	416.5413	7690.5054	2387.09	5133.29
	2	4	3238.2650	558.50562	279.2528	2349.5579	4126.9721	2451.29	3760.19
	3	3	3385.1567	1066.9328	615.9939	734.7486	6035.5647	2160.39	4112.89
	Total	10	3526.9100	984.60716	311.3601	2822.5645	4231.2555	2160.39	5133.29
Na	1	3	12.58933	8.185082	4.725659	-7.74354	32.92220	6.301	21.844
	2	4	6.48125	3.323256	1.661628	1.19321	11.76929	3.215	10.030
	3	3	6.10300	1.499236	.865584	2.37869	9.82731	4.923	7.790
	Total	10	8.20020	5.316912	1.681355	4.39671	12.00369	3.215	21.844
S	1	3	42.00267	14.626611	8.444678	5.66815	78.33718	25.968	54.614
	2	4	45.21725	14.336652	7.168326	22.40444	68.03006	37.022	66.618
	3	3	39.89967	15.906111	9.183398	.38670	79.41264	24.356	56.145
	Total	10	42.65760	13.336732	4.217445	33.11708	52.19812	24.356	66.618

Experiment 4: Statistical Analysis of Means. Concentrations Following Final Watering Regime

Significance level = 0.005.

<i>Element</i>		<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
Al	Between Groups	69722.456	2	34861.228	1.394	.309
	Within Groups	175017.932	7	25002.562		
	Total	244740.388	9			
Ca	Between Groups	679419.355	2	339709.677	.540	.605
	Within Groups	4401064.734	7	628723.533		
	Total	5080484.089	9			
Cd	Between Groups	.011	2	.006	.214	.813
	Within Groups	.184	7	.026		
	Total	.195	9			
Cr	Between Groups	2.662	2	1.331	1.772	.238
	Within Groups	5.259	7	.751		
	Total	7.921	9			
Cu	Between Groups	11.133	2	5.567	.869	.460
	Within Groups	44.852	7	6.407		
	Total	55.985	9			
Fe	Between Groups	2825767.206	2	1412883.603	1.770	.239
	Within Groups	5587770.715	7	798252.959		
	Total	8413537.921	9			
K	Between Groups	12823721.50 4	2	6411860.752	.048	.953
	Within Groups	933418351.5 07	7	133345478.787		
	Total	946242073.0 11	9			
Mg	Between Groups	410121.303	2	205060.652	.907	.446
	Within Groups	1582545.041	7	226077.863		
	Total	1992666.344	9			
Mn	Between Groups	3418.261	2	1709.131	.894	.451
	Within Groups	13384.309	7	1912.044		
	Total	16802.570	9			
Pb	Between Groups	2966295.853	2	1483147.927	.604	.573
	Within Groups	17182908.28 6	7	2454701.184		
	Total	20149204.13 9	9			
Zn	Between Groups	1225510.575	2	612755.288	.572	.589
	Within Groups	7499550.801	7	1071364.400		
	Total	8725061.376	9			
Na	Between Groups	82.807	2	41.404	1.68 9	.252
	Within Groups	171.619	7	24.517		
	Total	254.426	9			

Element		Sum of Squares	df	Mean Square	F	Sig.
S	Between Groups	50.313	2	25.156	.114	.894
	Within Groups	1550.503	7	221.500		
	Total	1600.816	9			

Experiment 5: Statistical Analysis of Mean Concentrations Based on Watering Regime

1: Optimally watered plants; 2: Waterlogged plants; 3: Droughted plants

Element	Watering regime	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	3	65.49533	29.566716	17.070351	-7.95246	138.94313	31.392	83.930
	2	5	83.06300	49.672132	22.214053	21.38690	144.73910	25.510	136.590
	3	3	67.12400	26.363124	15.220757	1.63437	132.61363	36.969	85.810
	Total	11	73.92482	37.117579	11.191371	48.98889	98.86075	25.510	136.590
Ca	1	3	5629.1767	292.72319	169.00381	4902.0120	6356.3414	5427.41	5964.91
	2	5	5159.7500	574.50284	256.92548	4446.4105	5873.0895	4453.71	5794.41
	3	3	5251.1100	564.81598	326.09666	3848.0293	6654.1907	4888.81	5901.91
	Total	11	5312.6918	505.81053	152.50761	4972.8837	5652.5000	4453.71	5964.91
Cr	1	3	.35033	.162189	.093640	-.05257	.75323	.175	.495
	2	5	.39040	.207407	.092755	.13287	.64793	.132	.639
	3	3	.33867	.246950	.142577	-.27479	.95212	.057	.518
	Total	11	.36536	.187777	.056617	.23921	.49151	.057	.639
Cu	1	3	10.7387	.57361	.33118	9.3137	12.1636	10.09	11.18
	2	5	6.9262	.21451	.09593	6.6598	7.1926	6.65	7.20
	3	3	8.7033	.48680	.28105	7.4941	9.9126	8.21	9.18
	Total	11	8.4506	1.69801	.51197	7.3099	9.5914	6.65	11.18
Fe	1	3	100.96333	21.359701	12.332029	47.90289	154.02377	76.492	115.864
	2	5	107.92960	62.791981	28.081428	29.96306	185.89614	42.909	184.254
	3	3	142.44267	69.496554	40.123854	-30.19634	315.08168	64.980	199.324
	Total	11	115.44236	54.260051	16.360021	78.98997	151.89476	42.909	199.324
K	1	3	53572.780	10802.492	6236.821	26737.902	80407.658	46151.635	65966.025
	2	5	39059.196	6642.516	2970.623	30811.423	47306.969	31679.025	44785.658
	3	3	57633.279	8230.079	4751.638	37188.628	78077.929	48221.004	63475.646
	Total	11	48083.105	11474.013	3459.545	40374.758	55791.452	31679.025	65966.025
Mg	1	3	4312.667	206.9347	119.4738	3798.612	4826.721	4080.9	4478.9
	2	5	3593.840	418.0334	186.9502	3074.783	4112.897	3126.5	4018.6
	3	3	3886.233	411.4785	237.5672	2864.064	4908.403	3622.9	4360.4
	Total	11	3869.627	457.5208	137.9477	3562.261	4176.994	3126.5	4478.9

Element	Watering regime	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Mn	1	3	109.4800	5.15654	2.97713	96.6704	122.2896	106.05	115.41
	2	5	120.9680	18.39898	8.22827	98.1226	143.8134	99.94	140.86
	3	3	95.6507	27.28957	15.75564	27.8596	163.4417	71.70	125.36
	Total	11	110.9302	20.26623	6.11050	97.3151	124.5452	71.70	140.86
Pb	1	3	7666.633	342.7703	197.8985	6815.145	8518.122	7397.4	8052.5
	2	5	6043.620	723.7607	323.6756	5144.952	6942.288	5258.6	6819.6
	3	3	5842.967	609.1301	351.6814	4329.804	7356.130	5426.7	6542.1
	Total	11	6431.536	971.6178	292.9538	5778.795	7084.278	5258.6	8052.5
Zn	1	3	3461.2900	228.90059	132.15582	2892.6694	4029.9106	3232.69	3690.49
	2	5	2331.7500	401.83447	179.70584	1832.8066	2830.6934	1896.69	2740.59
	3	3	2983.1900	360.22594	207.97655	2088.3392	3878.0408	2744.89	3397.59
	Total	11	2817.4718	592.93522	178.77669	2419.1325	3215.8111	1896.69	3690.49
Na	1	3	3.41933	1.669472	.963870	-.72787	7.56653	1.498	4.516
	2	5	8.80360	12.836967	5.740866	-7.13560	24.74280	1.455	31.541
	3	3	3.96367	1.871483	1.080501	-.68536	8.61269	1.803	5.077
	Total	11	6.01518	8.622342	2.599734	.22261	11.80775	1.455	31.541
S	1	3	42.64567	.373605	.215701	41.71758	43.57375	42.317	43.052
	2	5	21.27040	1.645883	.736061	19.22677	23.31403	18.801	22.964
	3	3	41.31567	6.849242	3.954412	24.30121	58.33013	33.416	45.595
	Total	11	32.56691	11.302040	3.407693	24.97410	40.15972	18.801	45.595

Experiment 5: Statistical Analysis of Variance of Concentrations Based on Watering Regime

Element		Sum of Squares	df	Mean Square	F	Sig.
Al	Between Groups	769.454	2	384.727	.237	.795
	Within Groups	13007.693	8	1625.962		
	Total	13777.147	10			
Ca	Between Groups	428820.938	2	214410.469	.805	.480
	Within Groups	2129621.959	8	266202.745		
	Total	2558442.896	10			
Cr	Between Groups	.006	2	.003	.069	.934
	Within Groups	.347	8	.043		
	Total	.353	10			
Cu	Between Groups	27.516	2	13.758	83.632	.000
	Within Groups	1.316	8	.165		
	Total	28.832	10			
Fe	Between Groups	3098.184	2	1549.092	.470	.641
	Within Groups	26343.347	8	3292.918		
	Total	29441.532	10			

Element		Sum of Squares	df	Mean Square	F	Sig.
K	Between Groups	771181719.172	2	385590859.586	5.656	.029
	Within Groups	545348174.499	8	68168521.812		
	Total	1316529893.672	10			
Mg	Between Groups	969972.096	2	484986.048	3.454	.083
	Within Groups	1123280.725	8	140410.091		
	Total	2093252.822	10			
Mn	Between Groups	1210.489	2	605.244	1.672	.247
	Within Groups	2896.711	8	362.089		
	Total	4107.200	10			
Pb	Between Groups	6368031.964	2	3184015.982	8.291	.011
	Within Groups	3072380.241	8	384047.530		
	Total	9440412.205	10			
Zn	Between Groups	2505521.524	2	1252760.762	9.921	.007
	Within Groups	1010200.192	8	126275.024		
	Total	3515721.716	10			
Na	Between Groups	71.718	2	35.859	.427	.666
	Within Groups	671.730	8	83.966		
	Total	743.448	10			
S	Between Groups	1172.422	2	586.211	44.690	.000
	Within Groups	104.939	8	13.117		
	Total	1277.361	10			

Experiment 5: Statistical Analysis of Mean Concentrations Based on Soil Depth

1: Shallow soil (20cm); 2: Medium soil (40cm); 3: Deep soil (60cm)

Element	Soil depth	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Al	1	3	88.07233	14.250236	8.227378	52.67278	123.47188	78.593	104.460
	2	4	45.38100	26.185457	13.092729	3.71409	87.04791	25.510	83.930
	3	4	91.85800	45.343588	22.671794	19.70623	164.00977	31.392	136.590
	Total	11	73.92482	37.117579	11.191371	48.98889	98.86075	25.510	136.590
Ca	1	3	5321.7100	311.04857	179.58397	4549.0225	6094.3975	4962.61	5507.31
	2	4	5111.0350	673.32139	336.66069	4039.6304	6182.4396	4453.71	5901.91
	3	4	5507.5850	479.58876	239.79438	4744.4523	6270.7177	4888.81	5964.91
	Total	11	5312.6918	505.81053	152.50761	4972.8837	5652.5000	4453.71	5964.91
Cr	1	3	.46867	.076121	.043948	.27957	.65776	.381	.518
	2	4	.28275	.220391	.110196	-.06794	.63344	.057	.495
	3	4	.37050	.212818	.106409	.03186	.70914	.175	.639
	Total	11	.36536	.187777	.056617	.23921	.49151	.057	.639

Element	Soil depth	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Cu	1	3	9.0520	1.96213	1.13284	4.1778	13.9262	7.03	10.95
	2	4	8.2478	2.06728	1.03364	4.9582	11.5373	6.65	11.18
	3	4	8.2025	1.50727	.75364	5.8041	10.6009	6.80	10.09
	Total	11	8.4506	1.69801	.51197	7.3099	9.5914	6.65	11.18
Fe	1	3	131.20733	27.559834	15.911677	62.74491	199.66976	114.734	163.024
	2	4	66.20500	31.099954	15.549977	16.71803	115.69197	42.909	110.534
	3	4	152.85600	54.707787	27.353894	65.80370	239.90830	76.492	199.324
	Total	11	115.44236	54.260051	16.360021	78.98997	151.89476	42.909	199.324
K	1	3	51019.553	9215.444	5320.539	28127.119	73911.988	43254.792	61203.187
	2	4	44451.566	16296.752	8148.376	18519.797	70383.335	31679.025	65966.025
	3	4	49512.308	9365.498	4682.749	34609.710	64414.906	43636.295	63475.646
	Total	11	48083.105	11474.013	3459.545	40374.758	55791.452	31679.025	65966.025
Mg	1	3	3907.467	248.4028	143.4154	3290.400	4524.533	3622.9	4080.9
	2	4	3761.750	701.9404	350.9702	2644.806	4878.694	3126.5	4378.2
	3	4	3949.125	372.1822	186.0911	3356.900	4541.350	3675.4	4478.9
	Total	11	3869.627	457.5208	137.9477	3562.261	4176.994	3126.5	4478.9
Mn	1	3	106.6707	17.09745	9.87122	64.1982	149.1431	89.89	124.07
	2	4	109.0950	11.22182	5.61091	91.2386	126.9514	99.94	125.36
	3	4	115.9600	31.49428	15.74714	65.8456	166.0744	71.70	140.86
	Total	11	110.9302	20.26623	6.11050	97.3151	124.5452	71.70	140.86
Pb	1	3	6643.233	1006.6054	581.1639	4142.687	9143.780	5560.1	7550.0
	2	4	6005.950	1366.3525	683.1763	3831.778	8180.122	5258.6	8052.5
	3	4	6698.350	472.3861	236.1931	5946.678	7450.022	6359.7	7397.4
	Total	11	6431.536	971.6178	292.9538	5778.795	7084.278	5258.6	8052.5
Zn	1	3	3162.7567	676.44552	390.54600	1482.3728	4843.1405	2400.19	3690.49
	2	4	2509.0400	745.43790	372.71895	1322.8820	3695.1980	1896.69	3460.69
	3	4	2866.9400	248.70170	124.35085	2471.2001	3262.6799	2687.39	3232.69
	Total	11	2817.4718	592.93522	178.77669	2419.1325	3215.8111	1896.69	3690.49
Na	1	3	4.35967	.667064	.385130	2.70259	6.01675	3.758	5.077
	2	4	2.31500	1.475736	.737868	-.03322	4.66322	1.455	4.516
	3	4	10.95700	13.848594	6.924297	-11.07920	32.99320	1.498	31.541
	Total	11	6.01518	8.622342	2.599734	.22261	11.80775	1.455	31.541
S	1	3	35.65467	14.673965	8.472018	-.79748	72.10682	18.801	45.595
	2	4	32.42475	12.992991	6.496496	11.75000	53.09950	20.479	44.936
	3	4	30.39325	9.877151	4.938576	14.67650	46.11000	22.141	43.052
	Total	11	32.56691	11.302040	3.407693	24.97410	40.15972	18.801	45.595

Experiment 5: Statistical Analysis of Variance of Concentrations Based on Soil Depth

<i>Element</i>		<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
Al	Between Groups	5145.851	2	2572.925	2.385	.154
	Within Groups	8631.296	8	1078.912		
	Total	13777.147	10			
Ca	Between Groups	314839.281	2	157419.641	.561	.591
	Within Groups	2243603.615	8	280450.452		
	Total	2558442.896	10			
Cr	Between Groups	.059	2	.030	.811	.478
	Within Groups	.293	8	.037		
	Total	.353	10			
Cu	Between Groups	1.496	2	.748	.219	.808
	Within Groups	27.337	8	3.417		
	Total	28.832	10			
Fe	Between Groups	16041.995	2	8020.998	4.789	.043
	Within Groups	13399.536	8	1674.942		
	Total	29441.532	10			
K	Between Groups	86790970.40 1	2	43395485.201	.282	.761
	Within Groups	1229738923. 270	8	153717365.40 9		
	Total	1316529893. 672	10			
Mg	Between Groups	76125.038	2	38062.519	.151	.862
	Within Groups	2017127.784	8	252140.973		
	Total	2093252.822	10			
Mn	Between Groups	169.098	2	84.549	.172	.845
	Within Groups	3938.101	8	492.263		
	Total	4107.200	10			
Mo	Between Groups	543.880	2	271.940	.329	.729
	Within Groups	6610.187	8	826.273		
	Total	7154.066	10			
Ni	Between Groups	340954.195	2	170477.097	.570	.587
	Within Groups	2394231.189	8	299278.899		
	Total	2735185.384	10			
Pb	Between Groups	1143699.899	2	571849.949	.551	.597
	Within Groups	8296712.307	8	1037089.038		
	Total	9440412.205	10			
Zn	Between Groups	747974.030	2	373987.015	1.081	.384
	Within Groups	2767747.687	8	345968.461		
	Total	3515721.716	10			
Na	Between Groups	160.674	2	80.337	1.103	.378
	Within Groups	582.774	8	72.847		
	Total	743.448	10			

Element		Sum of Squares	df	Mean Square	F	Sig.
S	Between Groups	47.583	2	23.791	.155	.859
	Within Groups	1229.778	8	153.722		
	Total	1277.361	10			

Appendix 6: Description of Site Features

Case Study 1 Soil Samples

Sample No	Sample Co-ordinate/ Context	Source	Feature
41	00; 15	Auger	Medial ditch
42	20; 40	Auger	Internal ditch/pits
43	00; 30	Auger	Entrance
44	2002	Excavated	Trench 2 subsoil
45	10; 20	Auger	Medial bank, inner edge, reverse anomaly
45R	10; 20	Auger	Medial bank, inner edge, reverse anomaly
48	00; 40	Auger	Medial ditch
50	1006	Auger	Trench 1 soil/small stony lens in section
51	00; 45	Auger	Outer bank
52	10; 45	Auger	Medial ditch
53	3003	Excavated	Trench 3
54	00; 00	Auger	Outer bank
55	20; 25	Auger	Interior
56	1002	Excavated	Trench 1 subsoil N end, poss. bank
57	20; 20	Auger	Interior
58	20;15	Auger	Interior
59	00; 10	Auger	Medial ditch
60	10; 40	Auger	Medial bank reverse anomaly
60R	10; 40	Auger	Medial bank reverse anomaly
61	00; 50	Auger	Outer bank
62	20; 55	Auger	Medial ditch
63	10; 25	Auger	Medial bank, inner edge
64	2003	Excavated	Trench 2 main medial ditch fill
65	20; 35	Auger	Internal ditch/pits
66	10; 55	Auger	Outer bank
67	2001	Excavated	Trench 2 topsoil
68	2006	Excavated	Trench 2 subsoil surrounding 2nd ditch cut
69	1003	Excavated	Trench 1 internal ditch fill/topsoil
70	20; 60	Auger	Outer bank
70R	20; 60	Auger	Outer bank
71	20; 30	Auger	Enclosure interior
72	00; 60	Auger	Enclosure exterior
73	2005	Excavated	Trench 2 2nd (later) ditch fill in section
74	10; 05	Auger	Medial bank
75	00; 05	Auger	Medial ditch

Case Study 1 Soil Samples (cont)

Sample No	Sample Co-ordinate/ Context	Source	Feature
76	3002	Excavated	Trench 3
77	10; 50	Auger	Medial ditch
78	1005	Excavated	Trench 1 subsoil, interior ditch edge
79	20; 05	Auger	Internal ditch/pits
80	00; 55	Auger	Outer bank
80R	00; 55	Auger	Outer bank
81	00; 20	Auger	Medial ditch
82	1001	Excavated	Trench 1 topsoil
83	10; 30	Auger	Medial bank reverse anomaly
84	00; 25	Auger	Medial ditch
85	10; 60	Auger	Outer bank
86	10; 00	Auger	Medial bank
87	2006	Excavated	Trench 2 subsoil surrounding 2nd ditch cut
88	10; 35	Auger	Medial bank reverse anomaly
89	20; 00	Auger	Internal ditch/pits
90	3003	Excavated	Trench 3 subsoil
90R	3003	Excavated	Trench 3 subsoil 3
91	10; 15	Auger	Medial bank reverse anomaly
92	3001	Excavated	Trench 3 topsoil
93	20; 10	Auger	Internal ditch/pits
94	00; 35	Auger	Entrance
94R	00; 35	Auger	Entrance
97	10; 10	Auger	Medial bank normal/reverse anomaly

Case Study 2 Soils

Sample No	Sample co-ordinate	Source/ Experiment	Feature	Category
1	0; 15	Auger	Inter-ditch	Inter-ditch
2	0; 20	Auger	Inter-ditch	Inter-ditch
3	30; 0	Auger	Inter-ditch	Inter-ditch
4	60; 20	Auger	Interior	Interior
5	40; 20	Auger	Interior	Interior
6	30; 20	Auger	Interior, negative patch	Interior
7	50; 0	Auger	Internal ditch	Ditch
8	10; 10	Auger	Inter-ditch	Inter-ditch
9	60; 0	Auger	Internal ditch	Ditch

Case Study 2 Soils (cont)

Sample No	Sample co-ordinate	Source/ Experiment	Feature	Category
10	0; 10	Auger	Outer ditch reverse anomaly/bank	Ditch
10R	0; 10	Auger	Outer ditch reverse anomaly/bank	Ditch
11	0; 5	Auger	Outer ditch	Ditch
12	40; 0	Auger	Internal ditch	Ditch
13	30; 10	Auger	Interior ditch at branch point	Ditch
14	0; 0	Auger	Enclosure exterior	Exterior
15	20; 10	Auger	Inter-ditch	Inter-ditch
16	60; 10	Auger	Interior	Interior
17	20; 20	Auger	Internal ditch	Ditch
18	40; 10	Auger	Interior	Interior
19	50; 20	Auger	Interior	Interior
20	50; 10	Auger	Interior	Interior
20R	50; 10	Auger	Interior	Interior

Case Study 3

Sample	Context	Source	Feature	Category
21	004	Excavated	Trench 4 natural?? Clay layer	Layer
22	018	Excavated	Trench 5 charcoal-rich subsoil	Natural
23	027	Excavated	Trench 1a ditch fill	Ditch
24	021	Excavated	Trench 3 natural	Natural
25	001	Excavated	Topsoil	Topsoil
26	006	Excavated	Trench 4, 5 silty clay fill	Fill
27	002	Excavated	Subsoil	Natural
28	025	Excavated	Trench 3 occupation layer	Layer
29	001	Excavated	Topsoil	Topsoil
30	004	Excavated	Trench 4 natural?? Clay layer	Layer
30R	004	Excavated	Trench 4 natural?? Clay layer	Layer
31	015	Excavated	Trench 2 ditch fill	Ditch
32	003	Excavated	Trench 4 organic floor layer	Layer
33	002	Excavated	Trench 1-4 orange-brown loamy clay	Layer
34	030	Excavated	Trench 3 fill	Fill
35	006	Excavated	Trench 4, 5 silty clay fill	Fill
36	005	Excavated	Trench 2 Fill	Fill
37	012	Excavated	Trench 2 brown loamy silt	Layer
38	012	Excavated	Trench2 brown loamy silt	Layer

Case Study 3 (cont)

Sample	Context	Source	Feature	Category
39	020	Excavated	Trench 1 occupation layer	Layer
40	007	Excavated	Trench 1 dark stained loamy clay	Layer
40R	007	Excavated	Trench 1 dark stained loamy clay	Layer

Appendix 7 Magnetic Susceptibility Data

Case Study 1 Plant Samples

Sample	Grown in Soil Sampled From	Treatment	Weight, g	Low Frequency MS	High Frequency MS	Frequency Dependent % MS
12	Topsoil	Optimum	5.40	0.90	6.80	-655.56
4	Topsoil	Dry	5.70	6.00	5.10	15.00
14	Topsoil	Wet	6.60	1.70	5.40	-217.65
19	Topsoil	Optimum	6.10	2.10	1.40	33.33
25	Topsoil	wet	5.40	2.50	8.20	-228.00
36	Topsoil	Dry	5.30	7.40	2.10	71.62
44	Topsoil	Optimum	5.30	3.10	0.90	70.97
45	Topsoil	Dry	5.40	4.70	4.20	10.64
46	Topsoil	Dry	5.60	7.40	1.70	77.03
33	Medial ditch	Optimum	5.60	5.40	-0.70	112.96
3	Medial ditch	Wet	5.50	3.20	3.00	6.25
6	Medial ditch	Dry	5.40	-1.00	6.70	770.00
29	Medial ditch	Optimum	5.20	3.00	5.30	-76.67
21	Medial ditch	Wet	5.20	-3.00	2.30	176.67
31	Medial ditch	Optimum	5.90	4.20	2.40	42.86
43	Medial ditch	Dry	5.00	12.80	3.70	71.09
50	Medial ditch	Dry	5.00	12.70	4.10	67.72
9	Earlier medial ditch	Dry	5.20	3.00	6.70	-123.33
27	Earlier medial ditch	Wet	5.10	5.60	6.10	-8.93
11	Inner ditch	Dry	5.00	1.30	12.00	-823.08
22	Inner ditch	Wet	5.10	8.60	5.70	33.72
1	Inner ditch	Optimum	5.00	4.80	1.10	77.08
23	Inner ditch	Dry	5.30	-0.50	7.50	1600.00
24	Inner ditch	Optimum	5.00	8.70	13.50	-55.17
26	Inner ditch	wet	5.00	6.20	7.30	-17.74
32	Natural	Optimum	4.70	6.00	2.20	63.33
41	Natural	Dry	4.30	83.40	30.00	64.03
13	Natural	Dry	4.90	4.60	11.90	-158.70
16	Natural	Optimum	5.20	4.70	2.10	55.32
17	Natural	Wet	5.60	7.10	-0.70	109.86
18	Natural	Dry	4.30	29.10	87.90	-202.06
20	Natural	Dry	4.60	13.30	11.80	11.28
30	Natural	Dry	5.00	6.40	7.90	-23.44
10	Natural	Wet	4.60	2.30	20.20	-778.26
47	Natural	Wet	4.80	13.10	3.30	74.81
48	Natural	Optimum	4.60	20.80	14.00	32.69
49	Natural	Optimum	5.20	6.40	9.00	-40.62

Sample	Grown in Soil Sampled From	Treatment	Weight, g	Low Frequency MS	High Frequency MS	Frequency Dependent % MS
51	natural	Optimum	4.50	33.10	16.70	49.55
52	natural	wet	4.60	9.00	17.70	-96.67
53	natural	wet	5.40	4.90	5.90	-20.41

Case Study 1 Augured Soils

Sample	Feature	Weight, g	Low Frequency MS	High Frequency MS	Frequency Dependent % MS
3	Exterior	13.3	16.8	17.9	-6.55
29	Entrance	13.3	9.7	14.4	-48.45
31	Entrance	13.4	15.2	12.5	17.76
32	Bank	13.8	21.1	18.6	11.85
33	Bank	15.3	72.9	70.4	3.43
35	Bank	14.4	37.9	35.4	6.6
36	Bank	14.2	29.2	26.8	8.22
13	Bank	15.0	29.6	27.8	6.08
14	Bank	13.7	27.5	26.8	2.55
17	Bank	13.5	17.5	16.5	5.71
22	Bank	15.0	47.3	49.0	-3.59
26	Bank	13.8	16.7	20.3	-21.56
20	Bank	13.7	23.4	23.9	-2.14
30	Bank	15.0	46.7	44.8	4.07
34	Bank reverse	14.2	61.2	57.3	6.37
8	Bank reverse	13.3	24.3	26	-7
10	Bank reverse	14.1	38.2	38.1	0.26
12	Bank reverse	15.7	65.8	64.1	2.58
37	Bank reverse	13.9	80.8	77.9	3.59
38	Ditch	13.7	14.6	11.4	21.92
1	Ditch	13.7	36.5	37.2	-1.92
4	Ditch	15.1	58.6	59.5	-1.54
5	Ditch	14.7	13.3	15.5	-16.54
6	Ditch	13.9	25.8	27.2	-5.43
11	Ditch	13.9	16.5	15.7	4.85
15	Ditch	13.3	13.1	13.2	-0.76
16	Ditch	14	44.2	43.5	1.58
18	Ditch	13.9	25.7	25.3	1.56
19	Ditch	14.3	23.7	23.2	2.11
23	Ditch	13.9	17.9	20.7	-15.64
25	Ditch	13.7	10.9	13.6	-24.77

Case Study 1 Augured Soils (cont)

Sample	Feature	Weight, g	Low Frequency MS	High Frequency MS	Frequency Dependent % MS
27	Ditch	13.9	15.3	18.7	-22.22
28	Ditch	13.7	9.4	13.8	-46.81
2	Interior	13.3	27.5	28.1	-2.18
7	Interior	15	26	27.5	-5.77
9	Interior	13.4	30.7	31.6	-2.39
21	Interior	13.8	31.1	25.7	17.36
24	Interior	13.8	20.9	23.9	-14.35

Case Study 1 Excavated Soils

Sample	Feature	Weight, g	Low Frequency MS	High Frequency MS	Frequency Dependent % MS
43	Topsoil	14.4	26.2	24.8	5.34
47	Topsoil	14.2	21.5	19.2	10.7
51	Topsoil	13.9	17.0	14.7	13.53
39	Natural	15.8	50.0	47.7	4.6
42	Natural	14.7	18.6	16.9	9.14
44	Natural	14.4	24.8	24.1	2.82
45	Natural	14.1	6.4	5.0	21.88
49	Natural	14.6	9.3	8.0	13.98
48	Natural	14.8	19.5	17.9	8.21
41	Natural	13.6	7.1	5.7	19.72
46	Ditch	15.6	12.7	11.4	10.24
40	Ditch	14.3	7.8	6.4	17.95
50	Ditch	14.1	21.4	19.1	10.75
52	Ditch	14.5	18.5	16.7	9.73
53	Ditch	14.3	37.1	33.3	10.24

Experiment 4 Plants

Sample	Start Treatment	End Treatment	Weight, g	Low Frequency MS	High Frequency MS	Frequency Dependent % MS
2	Wet	Optimum	5.80	1.90	-0.30	115.79
5	Optimum	Optimum	7.00	3.10	2.80	9.68
8	Optimum	Wet	6.10	2.50	4.30	-72.00
15	Dry	Optimum	5.30	4.40	4.50	-2.27
34	Optimum	Dry	6.80	2.70	1.50	44.44
35	Dry	Wet	6.70	1.20	1.00	16.67
37	Wet	Dry	5.80	7.20	-1.50	120.83
38	Wet	Wet	6.40	4.90	-1.40	128.57
39	Dry	Dry	6.90	4.90	0.40	91.84